By basic research the IEEE 802.15.4/Zigbee standard was identified as the key technology for a wireless sensor network (WSN) and Bluetooth for the wireless mines rescue communication system link. Additionally, alternative power supply technologies have been examined.

Wireless sensor network equipment have been developed, like sensors, interfaces and RFID devices, capable of operating in harsh mining environments, at underground propagation conditions and with ultra-low power consumption. Innovative technologies such as wideband chirp transmission schemes, ultra-low power microcontrollers and advanced networking protocols were necessary. By using standard-based interfaces, compatibility of different systems was achieved.

Several applications were developed, where the WSN equipment could demonstrate its capabilities. These were for example temperature monitoring at belt drives, rock stress monitoring and material tracking. Additionally, a solution has been developed to make the information of WSNs directly available on site by a wireless linked PDA.

Important enhancements of wireless technologies for personal sensor networks (PAN) were achieved. Small size wireless sensors capable of being worn by underground personnel provide continuous monitoring of health and environmental parameters. Localisation within the mine is possible as well. Portable devices for wireless voice communications have also been developed.

Operational trials have been carried out in several underground locations around Europe using the different developed technologies, i.e. WSN and PAN equipment and applications. The operational capability of the systems has been proven up to different levels. Some products are ready for marketing, for others firstly ATEX-approval or larger scale demonstration trails are intended.

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Researching the applications of open innovative wireless technologies (Rainow)

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1 TABLE OF CONTENTS

2 FINAL SUMMARY

This chapter addresses the most significant aspects on a task by task basis addressing project objectives, results obtained and their usefulness, plus possible applications and patents.

2.1 BASIC RESEARCH FOR ENHANCED AND FAIL-SAFE OPEN WIRELESS UNDERGROUND COMMUNICATIONS (SUMMARY WP1)

The general objective of this work was to carry out basic research on electromagnetic wave behaviour in confined spaces, such as mine roadways and to research and develop suitable energy sources (low-power or autonomous alternative power supply) for wireless applications (i.e. smart sensors, area networking, tracking, and safety communications). The most effective/appropriate technologies and communication procedures, e.g., Bluetooth, WLAN, ZigBee, NanoNet, etc. for these applications were to be identified.

2.1.1 Exploring the propagation of electromagnetic waves (Task 1.1)

Extensive tests were made to quantify the propagation of electromagnetic waves in underground mines and tunnels. Classical tunnel attenuation measurement and field mapping techniques were used, with CW ‘pure’ transmission at 2.3GHz and 5.8GHz including assessing coverage around items of mining equipment and plant. Tests were carried out at in a disused rail tunnel, a disused hard rock mine and in RAGs TBW test mine facility using a range of wireless technology equipment, to evaluate the overall performance in terms of throughput versus range. The measurement results were compared with those dervived from tunnel wave guide theory with reasonable correlation where the theory was appropriate. Measurements were also made of EM propagation at various frequencies through concrete. 2.4GHz was selected for future work. It was concluded that it was feasible to use this technology for through-the-rock transmission for rock stress measurement.

2.1.2 Examination of candidate wireless technologies (Task 1.2)

Assessment was made of which type of wireless sensor topology and technology might form the basis of future research and distributed sensor prototype system development. IEEE 802.15.4/Zigbee technology was proposed as the development platform for future low data rate sensing, monitoring and control applications. Additional technology types will be needed to address high data bandwidth applications, as required. Bluetooth has been selected for the wireless mines rescue communication link with provision for later upgrade to Ultra Wide Band (UWB) when available. UWB will have enormous potential when it comes to market.

2.1.3 Market analysis for smart sensor network technologies (Task 1.3)

Extensive work was carried out on the selection and appraisal of technology platforms suitable for the underground low power wireless sensor network applications identified within this project, e.g. smart sensor networks and active zonal position tracking systems. The need for development of an active ATEX approved RFID system was identified.

2.1.4 Specification of operational criteria for sensor networks (Task 1.4)

Technology options for compact, microstrip antennas were investigated. Any practical application of (embedded) wireless sensing will need to present a small physical envelope, with minimum mechanical vulnerability. The Planar Inverted-F Antenna and Electromagnetic Bandgap solutions were identified as being suitable for further development.

2.1.5 Researching alternative power supply techniques for smart devices (Task 1.5)

A review of alternative power supply technologies was completed in regard to achieving ‘true’ wireless performance beyond conventional battery supply. The aim was to eliminate the need for external power supply cables, which may not be available, and investigate means of power scavenging from other energy sources as a means of either replacing or at least extending battery supplies. Motion power harvesting was selected for further development. Alternative battery types were thoroughly investigated for the m-Comm wireless link and considerable work undertaken on circuit design to minimise power consumption.

2.1.6 Examination of available operating systems for sensor networks (Task 1.6)

Four suitable operating systems were identified and characterised, but some hardware is limited to the manufacturers’ proprietary systems. This is important to know for the further development work, but not envisaged as a problem.

2.2 DEVELOPMENT OF SMART WIRELESS SENSOR NETWORKS WITH INNOVATIVE POWER SUPPLY STRATEGIES (SUMMARY WP2)

The main objective of this work package was the development of smart, wireless sensors for several measurement applications. In addition to the development of sensors the advanced RFID-(Radio Frequency IDentification) technology was to be researched and used for development of an innovative resource tracking system. To ensure compatibility and interconnection to mine-wide communication systems the appropriate interface devices were also to be developed. Based on the results of the work package 1, ‘Basic research’, all autonomous wireless and sensor components were supposed to be equipped with low-powered and long-life or even alternative energy supplies, if applicable.

2.2.1 Smart wireless sensors for temperature, humidity, pressure, flow-rate, rock stress (Task 2.1)

Diverse wireless sensors and actuators have been developed as prototypes with their performance optimised for underground use. Two complementary wireless transmission technologies broadened the scope of potential target applications. This was also accomplished by use of versatile sensor interfaces expanding quantity of physical parameters which can be monitored. The devices fully exploit the potential of innovative ultra low power WSN technologies i.e. high resistance to multipath fades, in case of Chirp technology, and advanced routing / self healing properties of ZigBee networking protocol. Power management schemes enabled to achieve ultra low power operation and therefore long battery life resulting in long maintenance-free operation of wireless devices.

2.2.2 Alternative power supply for smart sensors and devices (Task 2.2)

The most promising energy scavenging technique from among many researched in course of WP1 was selected and employed to develop an alternative energy source aimed to power the wireless sensing applications. Theoretical modelling and laboratory tests with prototype components led to the final shape of the mechanical energy harvester suitable to be installed on winning machines. With use of a developed rechargeable battery buffering scheme, the prototype device is capable to work as maintenance-free energy source for low power wireless sensors.

2.2.3 Interface connectors and electronic control units (Task 2.3)

After the subsequent introduced improvements, thanks to information feedback from the mining end users, the prototype solution for the Data Acquisition Gateway (type DAG-1) was successfully developed. The device interconnects Wireless LAN network, ring topology based fibre optical backbone and multiple interfaces. It was certified as complying to ATEX directive. Apart from this also interfaces interconnecting wireless sensor networks based on ZigBee technology with cable transmission systems commonly used in European mines have been successfully developed. The prototype devices were extensively used during underground trials programme within WP5 and are an essential link between novel wireless systems and cable/optical fibre-based automation, control and monitoring applications.

2.2.4 Development of mobile and stationary intrinsically safe RFID-read and -write equipment (Task 2.4)

As result of research work carried out within this task both stationary (read/write) and mobile (tags) components of Radio Frequency Identification system were developed. The system is suitable for underground application and uses novel techniques to achieve maximum performance in conditions of mine underground workings. Identification tags employ active solution based on dual band operation (LF rx and VHF tx). Such an approach using additional techniques for reliable wake-signal detection enabled to achieve long read distance and fast tag information read rates as well as very low power consumption. Another part of research was dedicated to an approach, which perfectly complements to the abovementioned one. It is based on LR-WPAN (low rate wireless personnel area network). The solution uses ZigBee technology to provide zonal type of location and tracking. It complements the first solution with regard to performing dual role of localisation ID tags and source of information from personal/machine area sensors. Prototypes of both developed complementary identification and location solutions have been produced and used for development of applications for location and tracking (WP3 and WP4) as well as successfully proved in underground conditions (WP5).

2.3 DEVELOPMENT OF APPLICATIONS FOR THE UTILISATION OF SMART WIRELESS SENSOR NETWORKS (SUMMARY WP3)

The general objective of this work package was the development of applications for the utilisation of smart wireless sensor networks. They were to be developed for several areas in underground operating coalmines (temperature measuring on belt drives, transport of material, rock stress monitoring, personnel tracking). A further objective was the development of special software for Pocket PC's already in use underground that offer possible remote administration of shared underground operating sensor network components.

2.3.1 Temperature monitoring in the area of conveyor belt drives with sensor networks (Task 3.1)

Initial studies confirmed that carbon monoxide levels can remain very low until a late stage of combustion, so that used semiconductor sensor products lead to false alarm, triggered from sources like diesel vehicle emissions and blast fumes.

Thermal measurements at belt drives and also at suspicious idlers were carried out to find and analyse the areas with abnormal conditions. The measured temperature differences were found to be sufficient to be monitored by means of simple electronic sensors attached to gearboxes, engines and pulleys.

Valuations showed that the costs for the also considered alternative, i.e. to scheme with simple WSN based miniature temperature sensors within each roller bearing would exeed the practical benefit.

Within this task a redundant WSN-concept was developed by which significant improvements were achieved by on-line monitoring of gearboxes and drives. With the application of temperature and belt slippage sensors it is now possible to detect failures in advance and prevent serious incidents. The whole WSN-system inclusive corresponding hardware (sensors) and software (correlation between temperatures and speed of belt and drum surface) was developed and tested.

2.3.2 Self-organising networks for advanced monitoring of the infrastructure in mines (Task 3.2)

Besides the WSN hardware (sensors, interfaces, power supply etc.) and application related software, the way of how the work and data exchange of the components within the Network is organised was also to be developed. So within task 3.2 it was dealt with the corresponding steering and organization concepts of WSN's. A ZigBee based smart WSN has successfully been developed to a proof-of-concept stage for advanced monitoring of infrastructure.

Whilst Zigbee technology was proposed for the wireless sub-system, various topologies of higher level systems were studied. The implementation of long hop length TCP/IP daisy chain and mesh topologies were considered. Associated high-level software was developed in a way that it was scalable for different types and numbers of remote sensor WSN devices. Several steering systems were developed by use of TCP/UDP sockets of popular FTP and HTTP protocols. To enable easy deployment and management of the sensor network, the used web-servers embedded within the WSN's give access to sensor data via LAN/Internet conception. These interfaces mostly allow to assist in deployment and in management, to view data from defined group of sensors and others.

2.3.3 Monitoring Rock Stress (Task 3.3)

The predominant part of the already existing measurement technology for rock mechanical movements is carried out up to now with well-proved offline methods. To make such important measuring data available as fast as possible, however, the previous concepts must be adopted to the new WLAN- and Optical-Fibre based infrastructure of the mines. Since the physical relevant measured values for rock mechanics like pressure, extension and temperature change only very slowly and since only few measuring cycles with small bandwidths per unit of time are necessary for the measurement, the novel WSNs with economical battery operation were predestined in this case.

Besides the adoption of WSNs to this application, the corresponding sensors and sensor interfaces based on strange gauge have been developed and jobs to enable the system for ATEX certification were carried out.

2.3.4 Development of an underground RFID-based navigation and tracking system for machines, material flow and persons (Task 3.4)

For navigation and tracking a number of possible technologies and industry practice have been intensively reviewed and assessed. It was judged that active-type transponders using wireless sensor network (WSN) technology is the most versatile and cost effective solution to active underground tracking of personnel and vehicles in underground mines. A concept of the underground tracking system using WSN was developed and then used within task 4.6 for the development of a system for personnel tracking.

For mines where pocket PC's and WLAN access points are used, a particular smart solution was developed. A pocket PC equipped with a WLAN interface and a especially developed software can be tracked (and thus the carrying person) with an accuracy of only a few meters, based on the principle of field strength measurements.

For material tracking the complementary solution developed within task 2.4 was applied and underground tested within WP5 (task 5.2). The visualisation technology developed for that, is based on the tests of the localisation of pocket PC's using the WLAN access points mentioned above.

2.3.5 Wireless Sensors Access with PDA's (Task 3.5)

Every WSN must be able to communicate with external control systems. For higher platforms corresponding systems are used, which can transmit the gathered data from WSNs to the surface. However, for the local need of information, like the network state or the sensor conditions, it is necessary to offer the possibility for suitable Pocket-PC arrangements in underground mines.

Within this Task possibilities for implementation of fitting PDA's in the corresponding transmission concepts have been worked out. Beyond that, software tools were developed, that enable the measurement of the wireless-sensor values on site, take over the battery condition monitoring or which are able to check the performance and quality of data transmission issues.

2.3.6 Gathering and Collation of Operational Data for All Wireless Devices (Task 3.6)

Within this task the different WSN's have been checked concerning different conditions during operation. Here especially the EMI (Electro-Magnetic-Interference), effects of possible metal structures, audio interference and also wireless interference between the different WSN's were tested and documented.

2.4 Development of personal area networks for tracking, monitoring and guidance under health & safety aspects (Summary WP4)

The objective of this work package was the development of the technologies that allow the permanent connection of most of the underground workers to the mining communication backbone, permitting the monitoring and the assistance with human operations under the harsh conditions present in underground coalmines. This permanent connection allows the monitoring of the main "health" parameters (including the environmental ones), as well as a bidirectional interaction during both normal and abnormal situations. This interaction includes voice communication, telemetry, attitude / position monitoring and several levels of automatic signalling.

2.4.1 Development of smart personnel sensors for health and safety values (Task 4.1)

A design of a new personnel health monitoring system for mining application (according to ATEX) has been performed, obtaining a functional and operative prototype. Using the wireless technologies also researched during this project, this small size (weareable) device is capable of measuring the most important physiological human parameters (i.e. heart rate and body temperature) and providing this information to the global monitoring system through the PANs (personal area networks).

After this first development, some mining companies are interested on its use for monitoring the health parameters of the rescue team members. This product will be introduced on the market as soon as the certificates are obtained.

2.4.2 Smart personal sensors for environmental values (Task 4.2)

A prototype of a multi-sensor node has been developed. This small and weareable device include all the needed for measuring CH_4, O_2, CO and T values as well as for sending that information to the trunk monitoring system through a wireless PAN. Using saving energy techniques and the employ of low power hardware elements, the device is suitable to be battery powered.

Currently, some mining cap lamps manufacturers are interested on integrating this kind of multi-sensor node into this mining equipment. Further practical evaluation of applicability of the sensor set for assessment of environmental conditions in safe havens and during the rescue operations is envisaged within RFC-PR-07016 project EMTECH (Mine Emergency Support Technologies).

In addition to the above, the incorporation of environmental parameters measurement to the existing m-Comm system has been also researched, multiplexing the sensor data and the voice through the same 1 wire cable.

2.4.3 Integration of personnel voice communication (Task 4.3)

A miniature electronic module aimed to be integrated into a headset has been developed, mainly to provide voice messages to the user in function of the PAN sensor status. It is capable of receiving the data from the wireless sensors and warning to the person who is wearing it about for example, alert triggers, evacuation process instructions, etc.

In addition to the above, further functionality can be added to this module, becoming it a gateway between PAN and WLAN networks and being capable of establishing a bi-directional voice communication as well.

A prototype of headset including PAN connectivity was shown on 21st World Mining Expo and Congress in September 2008. It is expected to introduce the product into the market by means of Telvis Company.

Continuing with the work developed on RFC-CR-03003 project, a mixed communication interface for machinery data and voice has also been developed. It allows keeping the machinery operator continuously in contact with the main voice communication line of the mine as well as providing information about the machinery parameters to the monitoring and control systems.

2.4.4 Wireless adapting of mine rescue communication systems for hands-free operation (Task 4.4)

After performing an analysis in-depth of the key issues to add wireless support to the m-Comm system, the needed modifications of the current system to achieve that purpose has been designed, including noise cancelling elements, tone generators, microprocessor incorporation, etc. The result is a reliable system aimed for performing rescue activites capable of being connected to wireless voice devices using a Bluetooth interface. All the modifications performed on the original design were done according to ATEX standards requirements.

2.4.5 Development of a personal communication interface for WLAN access (Task 4.5)

A roadway amplifier capable of supporting wireless connectivity based on Bluetooth has been developed. Thanks to the use of this standard, the device is capable of being paired with any headset with Bluetooth connectivity located under its radio coverage area. This enhanced roadway amplifier is totally compatible with the current voice intercoms already installed in mines (based on RELIA-2000), acting as gateway between the current analogue voice trunk lines and the new digital portable wireless devices. Being some mining companies interested on it, this design is actually under certification process and it is expected to be commercialised by June 2009.

2.4.6 Personnel tracking and guidance in critical situations (Task 4.6)

A location and tracking software including Data Base storage has been developed. This software, is capable and in charge of gathering the position of the portable devices weared by the miners and shows their location in a graphical mine layout map.

In addition, a ZigBee portable device has been developed. This node is capable of providing to the system information about its position as well as a prediction of the status of the person who is wearing it, thanks to the incorporated acceleration, temperature and orientation sensors. In the other way, this device is capable of receiving information from the network in case of emergency situations, showing to the person information about the path towards the next refuge or safe way out.

The accuracy of the location system has been improved by means of appliying the mathematic model of the signal propagation through the tunnel.

As a result of this researches a new prototype is being manufactured in cooperation with a lamp cap company in order to integrate this location device into the mining lamps.

2.5 OPERATIONAL TRIALS PROGRAMME IN UNDERGROUND MINES (SUMMARY WP5)

The general objective of this work package was to test the equipment and applications that had been developed under real mining conditions. The feasibility of the technologies developed was to be prooved by testing several underground smart sensor networks. One key goal of this WP was to demonstrate the interoperability (including electromagnetic and software compatibility) of all the devices developed within the project. A further objective was to train the underground staff in handling smart sensor network components. It was also essential to assure that the critical wireless link that had been added to the mines rescue communications system will operate reliably in any mine location in Europe. So it was tested in proximity to all other wireless systems and devices. This meant visits to different mines in the EU.

2.5.1 Test-run, trials of Mines Rescue communications system in underground mines (Task 5.1)

The m-Comm mines rescue communications system successfully completed its underground trials and demonstrations during the period of the project. Reliability and availability of the whole mines rescue wireless system was paramount in the testing programme. To this end, wide ranging and detailed prototype testing, evaluation and simulated trials were scientifically designed and conducted.

Initial testing highlighted the potentially serious issue of signal loss due to body, head and close hand shielding, as would be found in a rescue condition where the operator may be required to crawl through a narrow opening, or similar. Despite such signal shielding losses the pre-production wireless units were able to operate over 10 m in all the simulated rescue conditions envisaged. Equally, no normally encountered co-channel interference rendered the system inoperable.

Underground tests, trials and demonstrations, mostly at Bath Stone Mine, confirmed the mines rescue communications system had met all the project’s stated key objectives. At 29’s working area for example, the wireless units worked from within windowless galvanized steel containers, with the door closed, to a distance of 10 m.

In operational trials, the wireless m-Comm system functioned as expected even with untrained operators. All rescue team members were new to the equipment and received very little training other than how to place the mobile unit in front of the breathing apparatus’ face mask diaphragm and operate the press-to-talk button. Limiting the mobile unit to the press-to-talk mode, functionally the same as for the handheld unit, made the wireless link operationally more intuitive and ensured inclusion of all parties on the system to all conversations. The loss of synchronization when the Bluetooth wireless units went out of range was an issue but the operators soon became aware of the range limitation. Automatic re-synchronisation takes only seconds when back in range.

The pre-production wireless equipment performed flawlessly. The only negative comment noted was the lack of sound level when operated next to an extraction fan. Both hub and mobile units were deemed to have adequate energy margins from the rechargeable Ni MH power pack to cover a typical 12 hour operational period.

In conclusion, the initial objectives and aims of the rescue communication part of the RAINOW project have been fully achieved and with better than expected results. The security of the wireless voice link within 10 m range of the portable forward ‘hub’ has been thoroughly tested in a wide range of confined and underground space. The results demonstrated that there is a higher than 90% probability of maintaining communications up to 15m and 95% up to 10 m. No wireless system can give a 100% availability figure given the unknown situations and environments that rescue communications units are expected to encounter.

2.5.2 Installation and trials of Smart Sensor Networks (Task 5.2)

A WSN of the smart wireless sensors developed within task 2.1 and which employ the chirp modulation was tested in the TBW training mine in Recklinghausen, Germany. Three different trials were carried out, among them one trail using a prototype leakyline antenna developed within the project IAMTECH (RFCR-CT-2004-00001). During the trials the measurement results were also online transmitted to the headquartes of RAG in Herne. The WSN worked very successfully over a distance of 100m with the standard antenna and 200m along the leakyline antenna.

The wireless mesh smart sensor system developed during WP3 were successfully tested. The smart sensor system was first of all tested to examine the physical performance and then later to examine the application performance. Various sensors were interfaced to the network and issues of real time monitoring, rapid deployment and scalability were investigated. A PHP web server display was developed that will automatically recognise new sensors joining the network and automatically display graphical data based on the information sent by the smart sensor itself.

The sensor network developed using the Nanotron Chirp-Transceivers was also successfully developed and tested at the TBW Test Mine in Germany, interfaced to rock stress transducers. The system was also interfaced to a PDA application using an ECOM i.roc to interface to the sink node via WLAN. Further tests were carried out at the Laciana coal mine training facility in Spain with the UCR-WIZ smart sensor network. These systems were interfaced to the existing SCADA networks and the sensor data were successfully collected across. Design and performance of final prototypes of ZigBee sensors for differential pressure, temperature and humidity was verified in underground workings of Guido mine Zabrze (Poland). Wireless network robustness was investigated in harsh conditions with successful results.

A programme of different trials was conducted in the German TBW training mine with the active RFID transponder system developed within task 2.4. for material tracking. All underground tests were successful and the feasibility of the system for underground application could be demonstrated.

2.5.3 Installation and trials of Personal Area Networks (Task 5.3)

The personal area networks developed for underground tracking of personnel were successfully installed and trialled at test mine facilities in Spain and the UK. The systems were evaluated from low level network performance through to the higher level application functionality in terms of storing the information on a database and displaying the locational information.

The underground tracking system was tested out against pre-defined ‘worst case’ operational conditions where the results showed overall good performance. These were conditions that include a high volume of mobile traffic (devices) at a slow travelling speed, moderate volume of mobile traffic at high speed, and finally a high volume of traffic travelling at high speed (e.g. locomotive carried multiple personnel). The network performed very well up until the point of having a high volume of devices travelling at high speed. These limitations and weaknesses of the network were intentionally highlighted, in order that these issues can be resolved during future developments of the application. In fact, the application in its present form will be more than suitable for most operational conditions.

Underground trials of personal health monitoring sensors and communication interfaces developed during WP4 were carried out in the Guido mine, Poland. Resilience to interference from other ISM systems and interoperability issues were investigated in real conditions. Multi-user operation and network congestion events were simulated proving reliable behaviour of developed sensors and interfaces.

3 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

This section covers the research approach providing a description of the experimental work performed on a task per task basis, highlighting the main results achieved.

3.1 OBJECTIVES OF THE PROJECT

The main objective of this project was to research, develop and introduce smart wireless sensor networks for improved monitoring and control of all underground operations (extraction, road heading and infrastructure). Besides operational issues like machines, tracking material transport, early fire detection, rock stress, etc., the miners themselves played a crucial role in this project. It was the intention to introduce an open wireless personal area network strategy to monitor the physical health of miners, to guide them in critical situations, to know about their whereabouts, and to provide an integrated personal voice and data communication capacity.

The technical key objectives of this project were:

a) to adopt open architecture wireless systems, which are strongly aligned with the ISO-OSI multi-layer framework model, and which can be supplied by a wider base of manufacturers.

b) to remove interconnectivity and interoperability problems resulting from proprietary systems and current "islands of automation".

c) to adopt harmonised data exchange standards which guarantee effective inter-system data exchange and data intelligibility.

d) to adopt integrated data and voice systems that exploit IP-based developments and offer the prospect of near-instantaneous mine-wide communications.

e) to implement a mine-wide communications capability which is fully compatible with existing high bandwidth, fibre-optic ring backbone systems.

f) to introduce wireless-sensor telemetry schemes based on high resilience mesh networking techniques.

g) to reduce costs associated with the continuous re-installation of systems, largely by replacing wires with flexible wireless schemes.

h) to introduce miniature, ultra low power 'smart' sensors (MEMS or motes) which operate from long-life batteries or with energy captured from the local environment.

i) to introduce and demonstrate distributed sensor schemes in several critical underground applications concerned with fire detection, leakage detection etc.

j) to introduce comprehensive zonal tracking and personnel monitoring using advanced RFID techniques, possibly based on multi-function wireless PAN technology.

k) to enhance the understanding of operational safety controls, certification and safety analysis associated with using programmable, wireless systems.

l) to monitor and telemeter key biometric parameters (‘vital signs’ of individuals), especially relevant to rescue workers and those involved in high heat stress activities.

m) to increase the resilience of response in emergencies, through the combined approaches of adopting high survivability networks, way finding guidance support and enhancements to emergency communication systems.

n) to gain better knowledge of UHF and microwave propagation in mines, leading to better performance in all systems, and specifically safety-critical systems such as stand-off remote control systems.

3.1.1 Basic research for enhanced and fail-safe open wireless underground communications (WP1)

The general objective of this work was to carry out basic research on electromagnetic wave behaviour in confined spaces, such as mine roadways, and investigate suitable wireless network stanadards and topologies for underground application. This WP also included research and development of energy sources for wireless applications. Fundamental to all intended research programme topics, i.e. smart sensors, area networking, tracking, and safety communications is the need for specific understanding of the behaviour and limitations of the technologies' radio propagation in underground applications.

The aim of this WP was to find the most effective/appropriate technologies and communications procedures, e.g., Bluetooth, WLAN, ZigBee, NanoNet, etc. for autonomously operating sensor equipment with low-power and to develop alternative power supply strategies.

3.1.2 Development of smart wireless sensor networks with innovative power supply strategies (WP2)

The main objective of this work package was the development of smart, wireless sensors for several measurement applications. In addition to the development of sensors, the field of RFID-(Radio Frequency Identification) was to be extensively researched since it plays an increasingly crucial role in other industries. The introduction of this technology, especially of the innovative techniques as expected results of the development work within the project, for solving logistical and infrastructure problems, will be a great advantage for mines in the European Community. Based on the results of Work Package 1, 'Basic research', all autonomous wireless and sensor components were supposed to be equipped with, low-powered and long-life or even alternative energy supplies.

3.1.3 Development of applications for the utilisation of smart wireless sensor networks (WP3)

The general objective of this work package was the development of applications for the utilisation of smart wireless sensor networks. Applications were to be developed for several areas in underground operating coalmines (temperature measuring on belt drives, transport of material, rock stress monitoring, personnel tracking). A further objective was the development of special software for already used Pocket PC's in underground that offer possible remote administration of shared underground operating sensor network components.

3.1.4 Development of personal area networks for tracking, monitoring and guidance under health & safety aspects (WP4)

The objective of this work package was the development of the technologies that allow the permanent connection of most of the underground workers to the mining communication backbone, permitting the monitoring and the assistance with human operations under the harsh conditions present in underground coalmines. This permanent connection allows the monitoring of the main "health" parameters (including the environmental ones), as well as a bidirectional interaction during both normal and abnormal situations. This interaction includes voice communication, telemetry, attitude / position monitoring and several levels of automatic signalling.

3.1.5 Operational trials programme in underground mines (WP5)

The general objective of this work package was to test the equipment and applications that had been developed under real mining conditions. The feasibility of the technologies developed was to be prooved by testing several underground smart sensor networks. One key goal of this WP was to demonstrate the interoperability (including electromagnetic and software compatibility) of all the devices developed within the project. On the basis of the trial results improvements were identified. A further objective was to train the underground staff in handling smart sensor network components. Mineworkers received dedicated training in the use of personal area networks. The computer programmes that had been developed were installed in mine control rooms to monitor measured values during the test-run period. All measured results and feedback from the underground staff were evaluated. It was essential that the critical wireless link that had been added to the mines rescue communications system was tested in proximity to all other wireless systems and devices. This meant visits to different mines in the EU; various test locations had been identified including TBW in Recklinghausen Germany, CSM Test Mine in Cornwall UK, GUIDO coal mine in Poland, and other operational coal mines in Spain. This way it could be assured that the system will operate reliably in any mine location in Europe. Likewise, other wireless systems were tested for interference problems. Trials and test results are fully reported.

3.2 Comparison of Initially Planned Activities and Work Accomplished

This section provides a comparison of initially planned activities and work accomplished. Any major deviations from the initial plan and their effects on the project are described.

3.2.1 Basic research for enhanced and fail-safe open wireless underground communications (WP1)

Tasks T1.1 and 2 involved more extensive trials than originally anticipated, and were hence extended. This extension was justified, given that the research and findings gained from this work had significant implications in all subsequent work packages. There were also minor deviations from programme in other tasks. Overall WP1 was completed 3 months later than scheduled without slowing work on the other WPs.

3.2.2 Development of smart wireless sensor networks with innovative power supply strategies (WP2)

The extensions within WP1 influenced the work within WP2, but didn't cause any significant negative impacts and were successfully fixed by rescheduling work on optimised sensing, signal conditioning and power supply techniques. Finally the wireless sensor devices reached their mature form and their performance was proved in laboratory tests as well as in preliminary tests carried out in underground conditions. Eventually, the functionality of versatile sensor/actuator was achieved which cover scope of potential applications beyond those few assumed at the project start. In case of task T2.2 the preconditioning research from WP1 indicated that the most promising and feasible energy sources for underground applications are mechanical energy scavengers. Therefore the development was focused strictly on this type of device and was completed with satisfactory results. Work on task T2.4 was postponed by two quarters but finally resulted in successful implementation of innovative 3D low frequency wake RFID solution. Task T2.3 was extended slightly by about a quarter but as result an ATEX certified solution for a Multi Switch was successfully accomplished.

3.2.3 Development of applications for the utilisation of smart wireless sensor networks (WP3)

The originally pursued technical solution to read out sensor data with a PDA turned out to be too laborious and expensive. However, an alternative solution was found and realised, which caused an extension of task 3.5 by six months. No negative impact to the project resulted from that, because the underground tests, scheduled within WP5 could still be performed before the project period ended.

3.2.4 Development of personal area networks for tracking, monitoring and guidance under health & safety aspects (WP4)

After finishing of tasks 4.1 and 4.4 , they were taken up again. In task 4.1 a new device of interest for the project was found and investigated. In task 4.4 the results of trials within WP5 were analysed and exploited. Both activities brought additional benefit for the project.

3.2.5 Operational trials programme in underground mines (WP5)

The T5.1 work programme was accomplished with only minor changes. These changes were selectively made to improve the test conditions thereby making the trials more efficient and allowing further iterative product improvement. These improvements resulted from both a consideration of ergonomic and underground mine trials. The trials were conducted at a stone mine, because the prototype units were not fully ATEX approved at that time. However, it was anticipated already within the original workplan that some tests may be limited depending on the ATEX approval. This is not considered to be a problem. After ATEX approval the system will additionally be tested within a coal mine anyway and the results will be exploited as planned.

Task 5.2 and T.5.3 were carried out as planned and defined in the original proposal. All partners were involved in conducting the various trials at several underground locations around Europe, essentially testing out the various smart sensor and personal area network systems as developed during the earlier work packages.

3.3 DESCRIPTION OF ACTIVITIES & DISCUSSION

This section describes the project activities and highlights the innovations made.

3.3.1 Basic research for enhanced and fail-safe open wireless underground communications (Activites WP1)

3.3.1.1 Exploring the propagation of electromagnetic waves (Activities Task 1.1)

A basic understanding of the behaviour of electromagnetic (EM) wave propagation in coal mine infrastructure was fundamental to success of this project. Hence, much of the initial research effort was devoted to this task. Firstly, background information on radio propagation, and its limitations, in confined spaces and tunnels was gained, mainly through researching past tunnel propagation measurements and published papers. Secondly, an extensive programme of underground testing and trials was undertaken. The use of numerical modelling for examining this subject was initially considered but rejected in favour of practical testing in realistic mining environments.

It is fortunate that the increased demand for wireless technology across all industries has forced companies worldwide to explore similar coverage problems in modern offices with high densities of metal cabinets and furniture. The office/building applications are mostly required for fast data transfer and with emphasis on anti-collision avoidance techniques.

The in-depth background search indicated that the multi-path propagation patterns in underground mines, particularly when encountering metal infrastructure, will cause the greatest difficulties in securing reliable transmission. Wireless digital transmission measurements are equally concerned with the consequence of multi-path, i.e., signal delay or arrival times and the relative multi-path total received power. It is the average delay time between multi-path signals that governs the maximum data rate in wireless transmission systems. The two standard methods of reducing this type of signal loss (known as fading) are frequency and space diversity reception. Frequency diversity is the main driver force behind ‘wideband’ wireless systems such as direct sequence and frequency hopping spread spectrum, e.g., Bluetooth and DECT products. These systems simply transmit a spread of frequencies wide enough to overcome any fading or drop-out by the fact that the different frequencies will create different, and generally non-coincident, fading patterns. Spread spectrum techniques are also better at implementing co-channel interference avoidance algorithms. The other diversity method is based on having two, or more, receiving aerials quarter of a wavelength λ (lambda) apart. In this way, the probability of both aerials receiving near zero signals at any one time is very small.

In addition, propagation in a small underground and possibly reflective space can have an effect on aerial performance (antenna coupling) and consequently signal strength. This problem is particularly acute when aerials are placed on the ground or near metal surfaces. Conductive water, as found in most mines, will also act as a conducting medium and again have a modifying effect on propagated waves. However, there are reported counter methods which will alleviate this problem, particularly when exploiting higher frequency wireless technologies.

A wide range of underground radio propagation and wireless networking tests were carried out. Transmission tests were conducted using a 2.3GHz and a 5.8 GHz continuous wave (CW) transmitter and various antennas for the transmission equipment. A Willtek hand-held spectrum analyser (along with a frequency converter for the 5.8 GHz measurements) was used for measuring the received signal strength. The tests were carried out in three locations; Ashbourne railway tunnel in the UK – a disused perfectly straight, smooth and empty tunnel, Camborne School of Mines (CSM) test mine – a hard rock test mine in the UK, and Maschinenübungszentrum (TBW) Training Centre – RAG’s replica coal mine test facility in Germany. These are shown in **Figure 3.3.1-1**.

These extensive tests were carried out along with a theoretical analysis of underground electromagnetic propagation in tunnels, comparing the results against a lossy dielectric waveguide model. A summary of the main findings is presented below:

Figure 3.3.1-1: Underground test locations: (a) Ashbourne railway tunnel (b) CSM test mine (c) TBW

2.3GHz transmission tests (using omni and directional gain antennas)

The tests at the Ashbourne railway tunnel demonstrated low attenuation rates versus distance along the straight railway tunnel. ‘Nodes’ and ‘anti-nodes’ caused by constructive and destructive interference at particular locations were observed.

The hard rock mine tests at CSM produced similar ‘straight’ tunnel attenuation rates. Irregular loss observations were made at junction intersections. Directional gain antennas were more efficient than omni directional antennas. For example a 5dBi patch antenna had lower signal attenuation than a 9dBi omni directional antenna. Also, lower attenuation rates around corners were obtained using directional antennas. This suggested improved coupling to the tunnel waveguide propagation modes.

The tests carried out at TBW were considered representative of European coal mine operating conditions. Interesting observations were made where lower attenuation rates were recorded around gradual circular tunnel bends, as opposed to sharp bends.

Various tests were carried out at both CSM Test Mine and TBW to evaluate the performance of a planar 5dBi patch antenna operating in close proximity to large metallic vehicles and plant. It was observed that this typically introduces up to 40dB additional loss.

Figure 3.3.1-2 shows the tests being carried out at CSM Test Mine and Ashbourne railway tunnel.

Figure 3.3.1-2: Conducting 2.3GHz transmission tests

5.8GHz Omni-directional antenna transmission tests

The 5.8GHz CW transmission tests were carried using 11dBi omni-directional antennas (transmit and receive) within the same reference locations as used in the 2.3GHz transmission tests at CSM test mine and Ashbourne

The CSM test mine 5.8GHz attenuation rates observed were very similar to the performance observed at 2.3GHz. An initial high attenuation rate was observed up to a critical point, usually around 10m distance, beyond which relatively low attenuation rates were obtained in a line-of-sight (LOS) straight tunnel. The initial step in attenuation was observed to be of the order of 30-35dB. This is marginally higher than seen in the 2.3GHz transmission tests.

The Ashbourne 5.8GHz results were again similar to the 2.3GHz results. Significant fluctuations of peaks and troughs in the received signal strength were observed, suggesting constructive and destructive interference. The overall nett attenuation rate was relatively low.

Comparison with tunnel waveguide theory

Electromagnetic (EM) waveguide propagation was investigated, in particular a lossy dielectric waveguide model for EM tunnel waveguide propagation characteristics at UHF and GHz frequencies.

Relatively good agreement was shown between theoretical predictions and measured data, taking into account mode attenuation, and other loss factors including wall tilt, roughness and antenna coupling. See **Table 3.3.1-1** and **Figure 3.3.1-3** below.

Test lcations	2.3GHz (dB/100m)		5.8GHz (dB/100m)	
	Theoretical	Measured	Theoretical	Measured
Ashbourne	2.65	5	6.34	4
CSM tunnel A	15.76	14	27.19	14
CSM tunnel B	15.16	18	26.95	18
CSM tunnel C	20.06	21	28.59	29
CSM tunnel D	15.41	32	27.002	32

Table 3.3.1-1: Total attenuation rates at 2.3GHz and 5.8GHz calculated vs. measured

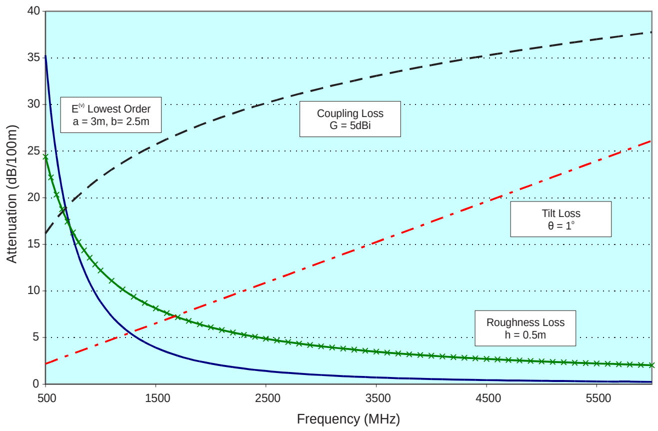


Figure 3.3.1-3: Calculated tunnel loss rates for CSM tunnel A

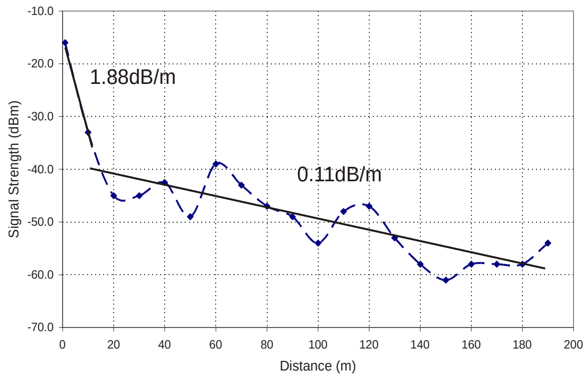


Figure 3.3.1-4: Example of two distinct attenuation rates (CSM Tunnel A -9dBi Antenna 2.4GHz

High attenuation rates at the higher order propagation modes also offered an explanation of the initial higher rate of attenuation observed in all tunnel propagation tests. These higher order modes have an attenuation rate in excess of 10dB/m, suggesting they would disperse after a few metres. The presence of more high order propagation modes in the first few metres which disperse beyond a certain point, would explain a higher initial attenuation rate, and why a low attenuation rate is observed beyond a certain critical point. **Figure 3.3.1-4** shows an example of the two distinct attenuation rates observed in all the tunnel propagation tests.

Whilst relatively good agreement was demonstrated between theory and practical measurements, the theoretical models are limited. Further work would require complex EM modelling software tools and was considered beyond the scope of this research project.

Test of propagation through concrete blocks

During the first months of the project, the IEEE 802.15.4 / ZigBee technology was identified by several partners as a key technology for development of personal wireless sensor networks.

One of the project objectives was development of sensors for rock stress monitoring. This application may require installation of sensors within the rock. The radio propagation behaviour of the 2.4 GHz band was unknown for this seting. Therefore, tests with different frequencies were carried out to determine their behaviour when transmitting through concrete blocks, in order to find out the feasibility of the propagation though a concrete wall of about 50 cm width.

The tests were performed using a specifically prepared concrete plug, built inside a pipe with a diameter of 2 m and of 10 cm wall thickness. The plug thickness was 50 cm, and the rest of space inside the pipe was empty. **Figure 3.3.1-5** shows the characteristics of the pipe, and **Figure 3.3.1-6** shows the pipe at the test site:

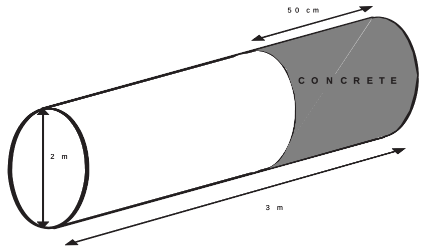


Figure 3.3.1-5 Dimensions of Concrete Pipe Used for Measurements

Figure 3.3.1-6 Photographs of Concrete Pipe Used for Measurements

Near Field / Far Field

To study electromagnetic wave propagation, a distinction must be made between near and far field conditions. Far field propagation is similar to the propagation of a flat wavefront, having an amplitude decrease which is inversely proportional to the square of the distance. This is achieved when the distance between the transmitter and receiver, in free space, is bigger than 3 times the wavelength.

Considering this condition to the case of the propagation though the concrete block, with a plug thickness of 50 cm, the frequency to achive the far field condition is equal to 1,8 GHz.

$$Far\ \ Field\ \Rightarrow d \geq 3\lambda$$
$$d = 50\ cm\ \Rightarrow\ \lambda_{FAR\,FIELD} = 16{,}67\,cm$$
$$f = \frac{c}{\lambda} = \frac{3 \cdot 10^8\ cm}{16{,}67\,cm} = 1{,}8\,GHz$$

Therefore, all the performed measurements were in near field conditions, so the classical propagation formula (Friis is free space) cannot be applied to calculate the received signal using the different transmission and antenna parameters. Therefore, the results were used as a comparison between the measurements outside and inside the concrete wall.

Measurements and results

The test was done using the following equipments:

- Spectrum Analyzer ANRITSU MS2711D
- RadioFrequency Transmitter from MARCONI

VHF: 5 – 200 MHz

Two "magnetic loops" were prepared for the tests, with the following characteristics:

- Loop: Square 20 x 20 cm
- Number of turns: 20
- Wire: 1 mm diameter copper

The antennas were connected to the equipment using 1.5 m (50 Ω), RG-58 coax cables with a male BNC connector. A 3dB signal attenuation is assumed with these cables. In addition, the connection to the spectrum analyzer required insertion of up to three connector adaptors, so an additional attenuation of 6 dB was assumed. Therefore a total attenuation of 9 dB was assumed for the later calculations.

Measurements in free space and across the concrete blockage were undertaken. In the case of free space, the distance between the transmitter and the receiver was fixed to 50 cm (the same as the concrete wall width). The transmitting antenna was vertically fixed, at a height of 30 cm above the floor. **Figure 3.3.1-7** shows the location of the transmitter for the free space test).

Figure 3.3.1-7: Location of transmitter for free space test

Figure 3.3.1-8: Photographs showing the location of the transmitter inside the pipe

For the measurements through the concrete wall, the transmitter was installed inside the pipe, close to the plug, and the receiver was at the other side of the plug. **Figure 3.3.1-8** shows the location of the transmitter inside the pipe ('a' and 'b'), as well as the place where the receiver was installed ('c' and 'd').

Table 3.3.1-2 shows the results obtained. As can be seen, at VHF frequencies and in near field conditions, using magnetic loop antennas, the received signal levels were better than in the free space condition (for this specific test), probably caused by the effect that the concrete plug had on the wave's polarization. It must be noted that in a near field condition the polarization is not known, independently of the way the antenna is designed. One disadvantage of the use of these low frequencies in near field conditions is the necessity of using big (in size) magnetic loop antennas, which may create a mechanical problem where the devices need to be inserted inside of a wall.

Table 3.3.1-2: Results from VHF tests

	FREE SPACE D = 50 cm (Near Field - H)	THROUGH CONCRETE D = 50 cm
F (MHz)	**(dBm)**	**(dBm)**
20	**-147**	**-117**
30	**-147**	**-108**
40	**-123**	**-104**
50	**-130**	**-111**
75	**-145**	**-121**
100	**-138**	**-96**
200	**-138**	**-103**

UHF: 500 – 1000 MHz

The measurements performed in the UHF band were done with the same equipment and in the same locations as the tests for the VHF band. The only change was the use of monopole antennas tuned to 2,4 GHz[1]. A big attenuation was assumed in some frequencies due to the antenna, but they are considered not too important, as the results were analyzed in relative terms.

The transmitter antenna was installed in a vertical position (vertical polarization), and the receiver antenna was fixed in different positions, as indicated in the **Table 3.3.1-3**. Some measurements could not be taken because the received signal level was very close to the noise floor. Nevertheless, it can be seen that the received levels are about 5 dB less in the propagation through the concrete than in free space. Three conclusions can be extracted from these experiments:

[1] A 2.4 GHz antenna was used for its easiness of purchase.

- Although at these frequencies the near field condition is still verified, the upper part of the band is close to the limit frequency to fit the far field condition (for this specific test, 1.8 GHz). Therefore a more predictable behaviour of the signal transmission is expected.
- Received signal levels, even without a perfectly tuned antenna, can be enough to maintain communication through the concrete plug.
- The required antennas are quite small compared to those needed for lower frequencies, so it is easier to get efficient antennas for embedded devices that can be installed inside a rock wall.

	FREE SPACE	**THROUGH CONCRETE d = 50 cm**
Freq. (MHz)	**RX Antenna VERTICAL V-V (dBm)**	**RX Antenna VERTICAL V-V (dBm)**
500	-90.5	-94
600	-83.2	-90.5
700	-91	-88.2
800		-84
900		-81.6
1000		-91.3

Table 3.3.1-3 Results from UHF tests

TBW Underground Radio Tests

Collaborative radio trials were carried out between MRSL, RAG and DMT, at RAG's TBW training facility, investigating the performance of 2.3GHz continuous wave (CW) transmission, and the underground behaviour of wireless networking technologies including; Bluetooth, Zigbee/IEEE 802.15.4 based technology, and WiFi variants, including the Embigence ATEX-certified WiFi access point. The objective was to investigate the characteristics of 2.4GHz ISM band transmission, and the performance and feasibility of candidate networking technologies within this type of environment, particularly with reference to low power wireless mesh networking.

A summary of the main findings from the TBW radio tests is given below:

TBW Underground Radio Tests Summary:

- Interesting observations were made in non-LOS (line of site) situations at TBW, where a lower signal loss was observed for tunnel bends with a more gradual curvature as opposed to more traditional 'square' junctions. Speculatively, the presence of the significant metallic infrastructure lining the tunnels appeared to enhance the waveguide effect compared with previous 'bare rock' environments (hard rock test mine and railway tunnel).
- The straight LOS tunnel test (TBW Main Tunnel), had more severe signal degradation than in similar previous tests (CSM and Ashbourne). The most likely cause of this was the presence of large metallic equipment, cabling and pipes causing RF obstruction.
- Mounting a planar antenna in close proximity to large machinery (conveyor) resulted in a total signal loss of 70dB. When comparing this overall loss to that observed in a straight LOS tunnel without machinery/plant present, this equates to an additional loss of around 40dB.
- A general summary of related wireless network tests confirms that all the ISM band wireless network technologies tested appear to offer a relatively robust solution in this environment. However, it was observed that Bluetooth, which employs a frequency hopping spread spectrum scheme, as opposed to the direct sequence spread spectrum techniques used in the various WiFi standards, is particularly robust in non-LOS transmission situations.
- EmberNet (Zigbee related) IEEE 802.15.4 low-power wireless mesh technology tests were carried out. The mesh network nodes were deployed in close proximity around a belt conveyor and in replica coal face environments, and were used to gather sensory data and distribute this in an analogous fashion to mine-wide mesh networks. The tests demonstrated that self-organising mesh networking provides a highly robust solution underground.

The research showed that 2.4GHz offers promising performance due to tunnel waveguide-like characteristics at these frequencies. Further to this, there is widely available technology operating in the 2.4GHz ISM band, most of which is standardised, paving the way for certified interoperability etc. However, a significant drawback of this is the issue of interference between the various standards e.g. between WiFi, Bluetooth and Zigbee, each potentially occupying the same channels. This was addressed within Task 3.6.

One method of addressing the issue of interoperability is by using a different frequency altogether. It is anticipated that wireless networking technologies that utilise higher frequency bands will become more widely available in the future. Companies such as Cisco Systems and LevelOne have been using dual 2.4GHz and 5GHz frequency bands to separate backhaul links in their mesh wireless access points. The 5GHz is usually employed for backhaul transmission.

3.3.1.2 Examination of candidate wireless technologies (Activities Task 1.2)

Wireless voice link for m-Comm

The wireless technology needs for the mine rescue communication system to be devloped under this Project are determined by the primary objective to secure reliable short range voice communications in any part of a mine. The characteristics of EM propagation within deep mine structures are however unpredictable, with the possibility of encountering random fading within metres of the transmitter, as concluded under Task 1.1.

In the examination of candidate wireless technologies it is first necessary to list the main requirements for the m-Comm wireless link, they are:

- Functional reliably as a wireless voice link over a range of 10m
- Battery powered, with a low current (mAmps) drain
- Should be able to be certified intrinsically safe to ATEX standard
- Compliant with the relevant European radio regulation and EMC standards under R&TTE
- Work along side other wireless systems
- Have the ability to be operated intuitively in a point-to-point or group fashion
- Small, lightweight and suitable for the working environment of a mine
- Exploit current technology and gain a cost advantage
- Have a reasonable product/technology life expectancy

In addition to the primary function of voice communication there should be the ability to send (automatically) limited data from the forward rescue team members to the base station.

This outline specification was also supported by the results of Task 1.3, 'market analyses for smart network technologies wireless technology'.

The first work was to examine in detail what were originally seen as the best technical options for the m-Comm wireless link, i.e. Circuit Design's WA-TX/RX, 960 MHz modules and a number of AIRWAVE 2.4 GHz audio short range modules. These were obtained and subjected to a number of basic measurements. Whilst both of these modules were effective in communicating over the required range (both had diversity reception options) they were too slow to switch-on. Turn-on times of over 300ms proved impractical, such transmit/receive delays making normal conversation difficult. Leaving both transmitter and receiver permanently powered increased power consumption well beyond the specification target. It also ruled out any possibility to manage power consumption, see Task 1.5. The technology of wireless microphone, wireless headphone and wireless surround rear speaker modules is firmly based on continuous operation.

Bluetooth and DECT technologies for this application had been initially discounted, because of their limitation in net or group operation. They were again reviewed. Bluetooth had the potential for the lowest power consumption and the higher frequency option. Bluetooth had the option for different power levels and, potentially, a Pico net operation as well as being a longer life standard product. A FREE2MOVE Bluetooth development product was evaluated in depth. It was programmed to operate a voice channel via codex and incorporate one digital channel for commands (m-Comm requires a press-to-talk signal). This performed well and had good immunity from interference from other devices operating at 2.4GHz. This technology was selected as the basis for the m-Comm wireless development. Reconfiguration of the internal programmable 'stack' for multiple unit operation (Pico net) was required and this was undertaken under section Task 4.4. The power saving ‘sniff’ mode did not give the expected power saving but its total 40 mA at 3 volts power consumption was acceptable.

The in-depth research into propagation, Task 1.1, and its limits underground revealed much parallel work in developing ultra wide-band, UWB, based technology.

UWB is a term for a classification of signals that occupy a substantial bandwidth relative to their centre frequencies. UWB signals, unlike conventional wireless transmission, consist of very short pulses of energy separated in time. As a result of the extremely short nature of the pulses, the effective bandwidth of the signal becomes very wide. This short pulse loses its carrier frequency identity and thus is also referred to as "Carrier Free". By virtue of the mathematics involved in determining the spectrum of a pulsed signal, the bandwidth of a signal increases as the pulse width narrows.

The low duty cycle of UWB results in very low average transmitted power and consequently low power consumption. When used for voice or data applications, UWB signals are very difficult to intercept and can support very high data rates. Unlike conventional voice or data EM signals, UWB signals have low susceptibility to multipath interference. In UWB, multipath signals result in replica pulses arriving at the receiver after a delay and are time selected in the receiver. By the same process UWB inherently provides precision ranging and localization.

UWB chip sets typically have few parts compared to conventional narrow band wireless devices. As UWB circuits are primarily digital, this technology lends itself to integration onto a chip. The market forces, primarily for higher data rates, are driving the development of UWB products, see table below, and may dominate future wireless technology products. It is more than likely that the established interface Standards, such as Blue tooth, will be maintained with the UWB upgraded products.

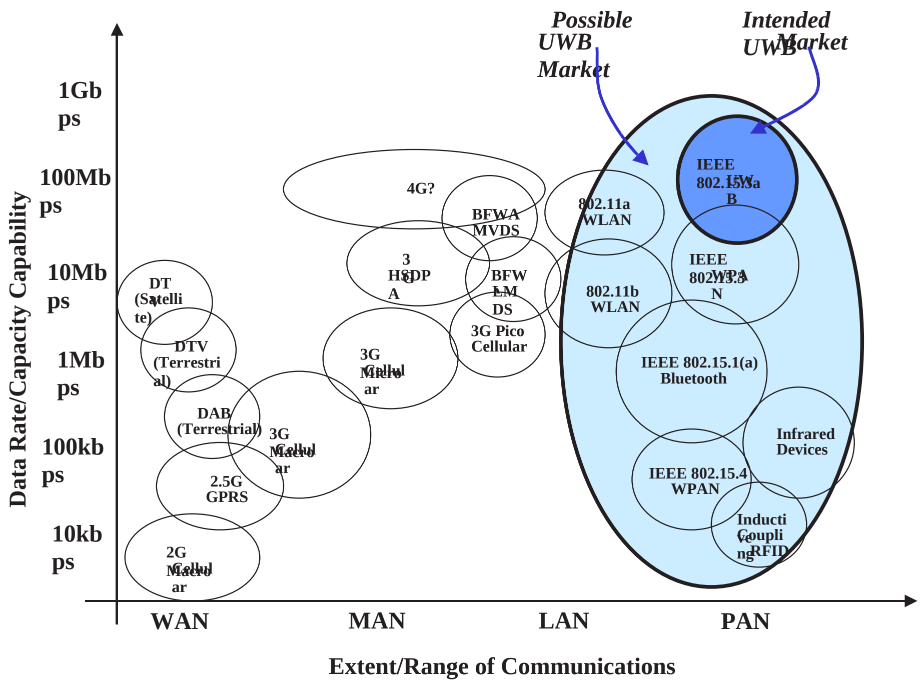


Figure 3.3.1-9: Key wireless technologies deployment in terms of range and capacity, highlighting IEEE 802.15.3a intended and possible UWB market deployment

The existing Bluetooth products, for example, will benefit from the migration to UWB technology, and data rates will increase over a hundred fold. RMT did not test UWB products within the period of the RAINOW project as commercial products were not readily available. It was considered expedient to pursue a Bluetooth platform in the expectation that UWB technology will emerge with similar Bluetooth, IEEE 802.15.1(a), standard interface.

Mesh wireless communication technology

Most partners involved in this project have identified IEEE 802.15.4 / ZigBee as the key technology to develop personal wireless sensor networks. The self-organising, self-healing, redundant pathways and scalability of mesh networks offer significant advantages in underground and confined space environments.

ZigBee/IEEE 802.15.4 are protocols based on standards that give the necessary network infrastructure for wireless sensor networks, whose basic design specifications are:

- Extended time of life without external power supply (wired)
- Low cost
- Low form factor (size)
- Complex communication topology
- Large number of devices connected to the same network

ZigBee radio modules are being developed in three RF bands: 868 MHz, 900 MHz and 2.4 GHz. All these are free use bands, but only 2.4 GHz is global (with limits imposed by the ITU – International Telecommunication Union) regarding to the maximum transmitted power and bandwidth.

The main characteristics of the ZigBee Specification are the following:

- 2 physical layer: 2.4 GHz and 868 / 900 MHz
- Data transmission rates: 250 kbps (2.4 GHz), 40 kbps (900 MHz) and 20 kbps (868 MHz). Data rates high enough for monitoring applications.
- Channel access by CSMA-CA (Carrier Sense Multiple Access – Collision Avoidance)
- Low power (up to several years life with batteries)
- Multiple network topologies: star, point-to-point, mesh
- Range: 50 m typical, up to 300 m with LOS (Line of Sight) conditions

For 2.4 GHz radio modules, ZigBee shares spectrum with other free-use technologies (Bluetooth, Wi-Fi), so special care must be taken at the frequency planning stage. **Figure 3.3.1-10** shows a comparison of the Wi-Fi and ZigBee spectra, which could serve as a guide for a channel selection:

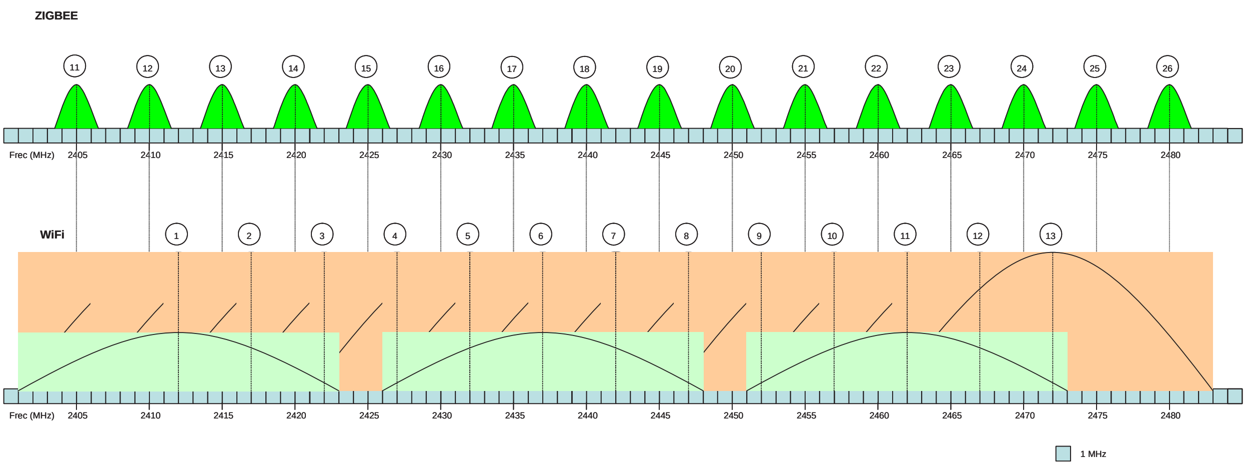


Figure 3.3.1-10: Zigbee vs WiFi spectrum

	BW	Channel Spacing
IEEE 802.15.4 ZigBee	3 MHz	5 MHz
IEEE 802.11 WiFi	22 MHz	5 MHz

ZigBee is a more robust technology than any other sharing the same frequency band. **Figure 3.3.1-11** shows the BER (Bit Error rate) vs SNR graph.

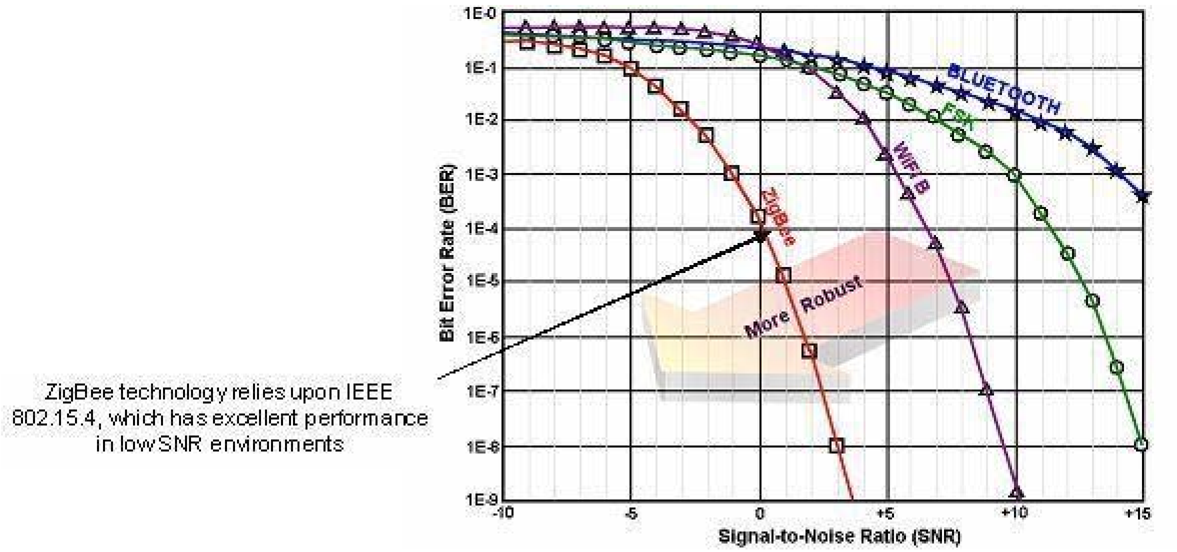


Figure 3.3.1-11: Bit Error Rate versus Signal-to-Noise Ratio

Types of Node

There are two types of node in a wireless sensor network, regarding the functionality:

- FFD (Full Function Device)
- RFD (Reduced Function Device)

Related to the function of every device in the network, three types are identified:

- Coordinator. It is a FFD device, in charge of constituting the network and managing the communications between all the network components. Always will have the address '0000'.
- Router. It is a FFD device that allows other devices to be connected to the network and sets the path for the messages towards the Coordinator.
- End Device. It is a RFD device that only can communicate with FFD devices.

The main difference between ZigBee/IEEE 802.15.4 and other technologies is the capacity to set up a hierarchical association structure between the different types of network elements, instead of simple master – slave connections. This feature allows extending the network range as much as needed.

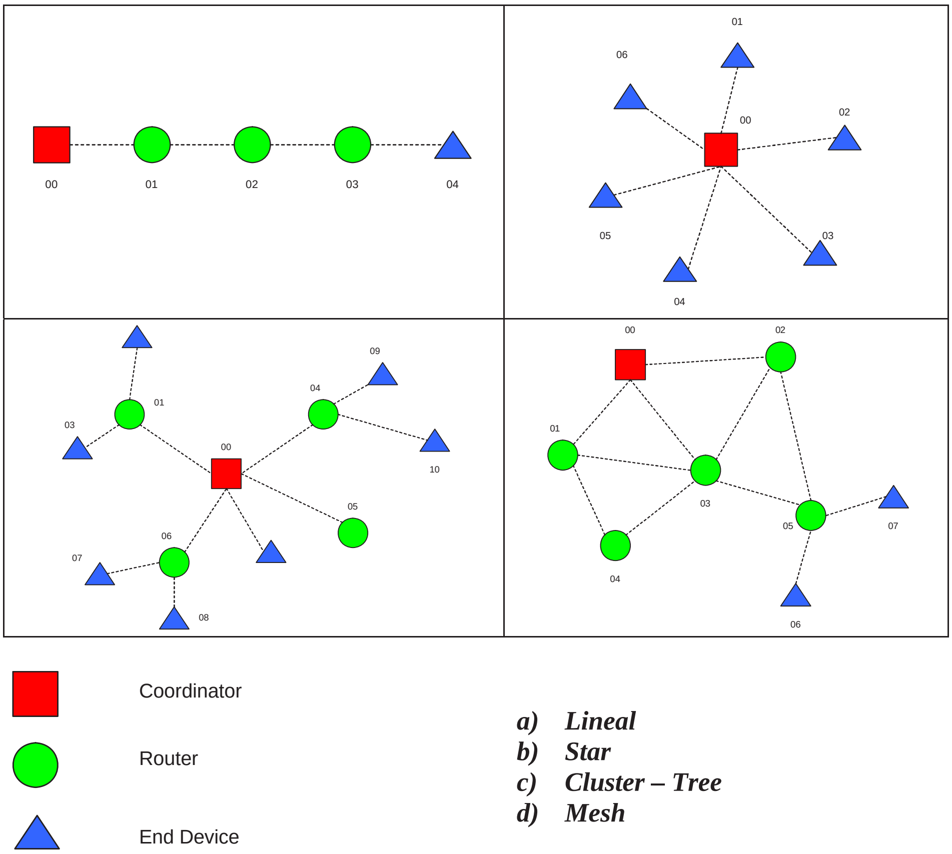
Network Topology

The structure of a wireless sensor network cannot be predetermined in most cases, due to variance in the sensor positions and the radio propagation characteristics during network establishment.

The type of topology will be determined by the kind of nodes or devices that form the network, and could be one of the following (as shown in **Figure 3.3.1-12**):

- Linear
- Star
- Cluster/Tree
- Mesh. As stated before, the main feature of ZigBee specification is the ability to set up multiple communication paths between the sensor nodes and the network coordinator. Mesh topology offers a total connectivity between all the Routers (FFD) and the Coordinator.

As has been previously discussed, the Zigbee/IEEE 802.15.4 related low-power wireless mesh networking technology was identified as a suitable candidate for the proposed underground smart sensor applications The applications were originally developed using the Ember EM2420 development kit, both with EmberNet (proprietary) and EmberZNet (Zigbee compliant) software stacks, and was then migrated to the later release of the EM250 tools. There remain complex issues pertaining to the dynamic behaviour and establishment of mesh networks



a) Lineal
b) Star
c) Cluster – Tree
d) Mesh

Figure 3.3.1-12: Network Topolgies

There are inherent trade-offs between static and dynamic (convergence) performance and device complexity (and thus device stack size). One of the research outcomes is that there are technical advantages in considering the proprietary EmberNet stack over Zigbee. The EmberNet stack employs a Gradient routing mechanism, which updates binding/routing information quickly in dynamic and mobile mesh networks. The Zigbee standard operates efficiently with static mesh networks using a 'Cluster Tree' topology, but slows significantly if the network becomes mobile and binding information has to be regularly updated. A transport layer has also been built into the EmberNet stack, which provides end-to-end acknowledgements with retries and time-outs. Zigbee provides acknowledgements but this is not directly related to individual messages. Therefore, the transport layer enhances the overall message delivery robustness.

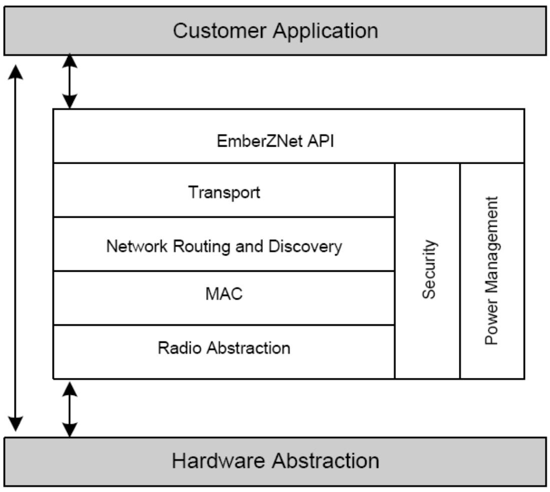


Figure 3.3.1-13: EmberZNet Stack

Ember Corporation is a key promoter of Zigbee and have developed their own version of the stack (**Figure 3.3.1-13**, above), EmberZNet, with features including a transport layer. Mobility is anticipated to be one of the points to be addressed in subsequent versions of the Zigbee standard.

Data throughput in a Zigbee network depends on network density, number of hops, frequency of messages, packet sizes, whether security is incorporated etc. At 2.4GHz the raw data rate is typically around 250kbps. However, allowing for network overheads the maximum throughput is typically 20 to 40kbps. In large complex networks, especially dynamically changing networks, Zigbee network throughput can be reduced significantly. The EmberZNet stack will achieve 45kbps throughput over 1 hop, and will maintain a throughput >25kbps over 5 hops.

3.3.1.3 Market analysis for smart sensor network technologies (Activities Task 1.3)

Wireless Sensor Network (WSN) Development Platform Considerations

As previously discussed, Zigbee/IEEE 802.15.4 related low-power wireless mesh networking technology is the most suitable candidate for the proposed underground smart sensor applications. The self-organising, self-healing, redundant pathways and scalability of mesh networks offer significant advantages in underground and confined space environments. There are a number of Zigbee/IEEE 802.15.4 related technologies as well as non-standard low power wireless mesh networking technologies aimed specifically at wireless sensor network (WSN) applications. A comparison of key WSN technologies and the associated development platform tools was carried out. A short description of each of the technologies is also given below.

Summary of WSN Development Platforms:

- *Ember*: There are three variants; EM2420 (which is currently being phased out), EM250 (single chip solution) and EM260 (requires separate host interface). Initially employed the EM2420 development platform with the EmberNet software stack and then later switched to the EM250 and EmberZNet stack (fully Zigbee ratified).
- *Telegesis*: In partnership with Ember, Telegesis is offering two mesh network radio modules; ETRX1 based on Ember’s EM2420, and ETRX2 based on Ember’s single chip EM250. Using the Ember development tools these can be fully programmed for application development. As a further option, Telegesis offers an AT-based command approach, which requires a separate PC or microcontroller host interface.
- *Crossbow Motes*: Mote technology has been established for some time now (particularly for military remote reconnaissance applications). The motes are very well suited to low power, very small physical envelope size sensor applications. Crossbow offers Zigbee ratified motes operating at 2.4GHz. The company has received major investment input from Intel and Cisco, and hence is expected to become a major technology supplier.
- *nanoTRON*: A non-standard wireless network system based on CHIRP modulation technology. The technology claims to offer extremely high physical performance; high data rates, very low power and robust transmission in harsh environments. It is unclear how the networking or mesh capabilities compare to other established WSN technologies.
- *MaxStream*: Offering XBee and Xbee Pro modules. The XBee Pro offers enhanced RF performance; up to 18dBm transmission power, and increased sensitivity. This technology also has mesh capabilities through the Freescale Zigbee software stack.

Newtrax: This Canadian-based company is offering non-standard high performance low power wireless networking devices for mining applications. These currently operate only at 915MHz, with a 2.4GHz release planned.

3.3.1.4 Specification of operational criteria for sensor networks (Activities Task 1.4)

A brief study of existing RF mining devices and systems was undertaken together with a review of the state of the art in Polish mining RF systems. The efforts were focused on investigation of potential sources of interference for envisaged wireless data transmission in the 2.4 GHz ISM band. Laboratory tests of the representative wireless equipment were carried out in the anechoic chamber at EMAG Katowice.

The results of these tests proved that:

- the worst source of interference were Bluetooth modules causing high degradation of link quality for 802.15.4 (ZigBee) and 802.11b/g (WiFi),
- tests proved high immunity of 802.15.4 transceiver modules both to inband and co-channel interfering WiFi signals, as well as to outband interfering signals from U/VHF - 170MHz, 433MHz, 1.9GHz systems. Even in the case of relatively high RF power levels, up to +23dBm, neither increase of BER nor receiver blocking phenomenon was observed.

It was concluded that:

1) 802.15.4 seems to be a good choice for smart sensor transmission because of both field proven robustness in the industrial environment and very good coexistence with WiFi - which is intended to be used as a “broadband” gateway to the backbone communication network.

2) The Bluetooth frequency hopping modulation scheme can degrade to a high extent WiFi and ZigBee transmission. This is a “real-world” problem as there is at least one type of Bluetooth Class 1 – based control system for shearers already implemented in some European mines. Due to its high output RF power it can be a serious source of interference for other 2.4GHz systems located in the longwall area. This could cause higher retransmission rate / higher output power demands of ZigBee nodes and therefore shorten significantly battery life of smart sensors. It could also decrease the throughput of neighbouring 802.11 networks, which can result in insufficient bandwidth and stability required for streaming services such as VoIP transmission, which is essential for the equipment to be developed in WP4. To overcome the problem, use of Bluetooth devices, especially high power - Class 1 type and below v.1.2 specification, should be limited to a minimum in new designs. Also it must be considered whether some of the mining legislation procedures regarding certification of RF products for mining industry should be updated to avoid future interference problems.

3) The results indicate that the previously envisaged use of Bluetooth devices for a PAN network to be developed under WP4 should be abandoned and some less interfering solution should be chosen. The best possible alternative for replacement of Bluetooth could be use of simple FSK/GFSK low power ISM transceivers or 802.15.4 /ZigBee.

The specifications for ensuring compliance with the requisite European R&TTE Directives and EMC standards were examined. To overcme the potential conflict of spectrum use for the m-Comm wireless application, the low power Bluetooth Class 2 hardware using version 2 software was selected. The provision of a data input interface for the wireless mine rescue communication system was examined with important input from with project colleagues at MRSL (see Tasks 4.1, 2 and 3).

Compact and microstrip antenna technologies technical review

Antenna technology options which might be suitable as the basis of a compact, low profile antenna system suitable for mounting on machines and in other mechanically vulnerable locations underground were examined. This was in response to the recognition that helical or monopole antennas are fundamentally susceptible to damage in an underground or confined space environment.

The following points give a summary of the findings:

1. Compact planar antennas offer a range of potential advantages including compactness, low-profile, ease of fabrication, array formation, efficiency and mechanical robustness.
2. Important characteristics of planar microstrip antennas were reviewed. This highlighted potential weaknesses, along with various microstrip antenna design enhancements which may be used to overcome the issues raised.
3. Potential candidate antenna technologies include shorted patch antenna, folded SPA, PIFA and EBG structures.
4. Mounting of antennas in close proximity to large metallic substrates could pose significant limitations on antenna performance.
5. Of the antenna technologies identified, the PIFA (Planar Inverted-F Antenna and EBG (Electromagnetic Bandgap) solutions were proposed for further development as candidates for mobile underground applications.

3.3.1.5 Researching alternative power supply techniques for smart devices (Activities Task 1.5)

A review of alternative power supply technologies was carried out, in regard to achieving true wireless performance of smart sensor devices in locations, or environments, where an external power source is not readily available. Power scavenging or "harvesting" techniques can be used to either replace or extend battery supplies.

A summary of the main findings is presented below:

1. The review gave consideration to three main potential operating environments of the smart sensor technology; (1) vehicle or plant mounted sensors (2) body worn sensors, and (3) environmental sensors.
2. A range of both commercially available technologies and concepts in early research stages were evaluated.
3. Vibration scavengers or linear motion scavengers are perhaps an optimal solution for machine or plant mounted sensors. There are vibration systems commercially available and RAG have developed a dynamic linear motion system (see below).
4. As an alternative to battery (e.g. cap lamp battery), or back-up power sources, potential candidates for generating power for body worn sensors include; hand-crank generators, generating energy from walking or temperature differential scavengers.
5. Environmental systems remote from sources such as temperature differentials or vibration could potentially make use of other energy sources e.g. air flow, or compressed air supplies.

Table 3.3.1-4 shows the different energy harvesting methods in terms of their power density and their place of installation with reference to a common area and/or volume.

Energy Source	**Special Conditions**	**Estimated Power** (per cm^3 resp. per cm^2)
Light	Not always available underground Mostly big planes are necessary	~ 10µW – 15mW (External area: 0,15 – 15 mW) (Indoors: < 10µW)
Vibration	Variability of vibration	~ 1µW – 200 µW (Piezoelectric: ~200µW) (Electrostatic: 50 –100µW) (Electromagnetic: < 1µW)
Temperature	Small thermal gradients	~ 15µW (10°C gradient)
Air Flow	Not always available	~ 65µW/cm^2 Air Flow 1 m/s
Dynamic motion	Not always useable for energy harvesting	~ 300 µW (Electromagnetic)

Table 3.3.1-4: Estimated power for different ambient energy sources

Light and thermal gradient energy are unlikley to be appropriate in coal mining situations The occurrence of these ambient energies in underground areas is rare and so enough power would not be collected for supplying the target devices.

The use of the airflow is certainly a possibility for powering electronic devices in remote areas in underground mining, especially as airflow in most mine workings is essential. Complicating factors include high moisture and the presence of dust inducing a necessity of intense maintenance.

The use of vibration or motion energy seems to be the best approach for a mining oriented energy harvesting system provided it can be mounted on moving equipment. The first choice would be the piezoelectric effect for higher frequency vibrations and the electromagnetic effect for lower frequency accelerations as the highest energy densities are available through these techniques.

Figure 3.3.1-14 Real vibration measurements on plough and conveyor

The electrical behaviour of a vibrating piezoelectric element or an accelerated electro-magnetic system can be modelled to first order as a sinusoidal current source. The magnitude of the polarized current depends on the mechanical excitation levels.

For the theoretical calculations of the energy amounts available from the movements of a face conveyor or a mining plough, the key parameters such as acceleration, velocity, acceleration distance and stimulation frequency had to be measured on real machines. Therefore a battery based semiconductor memory unit with matching acceleration sensors was fixed on a conveyor and a plough and the actual accelerations during the use were acquired. (**Figure 3.3.1-14**)

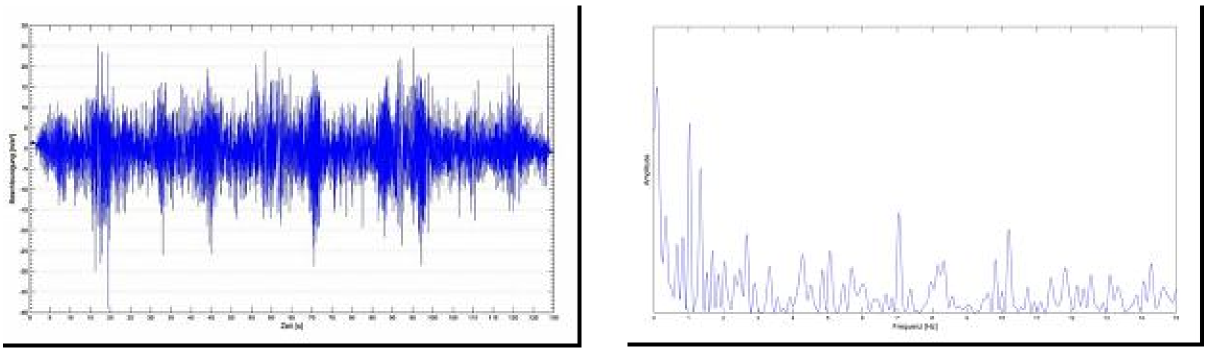


Figure 3.3.1-15: Vibration measurement and derived frequency spectrum of the plough

Due to the arrangement of the tractive chain, different grades of the coal and different electrical drive systems the plough doesn't move linear along the face and makes rather translational movements instead. This led to the measurement result shown in **Figure 3.3.1-15** for one plough run along the face with a length of approx. 300 meters.

For the design of the planned energy transformer it was necessary to find representative frequencies with a high density of energy. Therefore a fast Fourier-Transformation of the vibration spectrum of **Figure 3.3.1.14** was made. This offered then two useable maxima at 1,0Hz and at 1,3Hz. By further integration of the acceleration values and averaging the associated velocity and extension values were found to be:

Vibration extension x_e:	often < ± 30 mm	(average value: ± 12,4 mm)
velocity v_e:	often < ± 0,2 m/s	(average value: ± 0,093 m/s)
accelleration a_e:	often < ± 1,5 m/s²	(average value: ± 0,726 m/s²)
stimulation frequency f_e:	0,9 … 1,5 Hz	

The use of low energy harvesting systems poses additional challenges. There are issues not easy to solve related to the storing, conversion and efficient use of these low power sources. In addition to the technical issues (voltage levels, energy storage and conversion); also safety for use in potentially explosive atmospheres aspects must be carefully considered when designing such power supplies.

Effectively, the above low power sources cannot be used directly in many cases, for they supply too low a current and perhaps not at the right voltage. Therefore some kind of energy conversion (usually voltage elevation) and energy storage or buffering may be needed; together with an additional regulator in the utilization side.

In some cases, the design of the energy-harvesting + energy-storage pair can eliminate the need of energy conversion, but this is not always possible.

When energy conversion is required, the use of switched energy transformers, which can be either of inductive (usually known as switched boost regulators) or capacitive (switched capacitor converters) type is the best option in terms of simplicity and efficiency.

Some very low power, low voltage switched regulators are available in the market, having quiescent currents as low as 1.5 μA. However, they have the disadvantage of having relatively poor efficiency (see **Figure 3.3.1-16 and 17**).

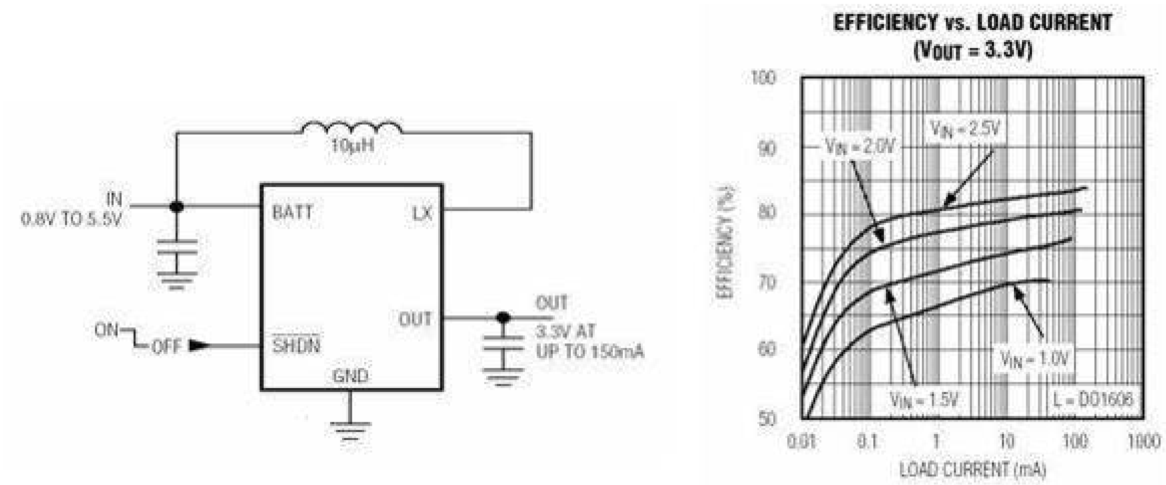


Figure 3.3.1-16: Inductive switched boost regulator: Circuit diagram and efficiency

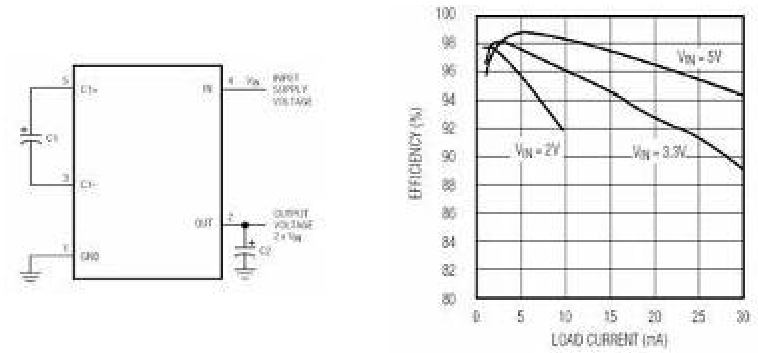


Figure 3.3.1-17: Switched capacitor voltage doubler: Circuit diagram and efficiency

The latest type (switched capacitor converters) has several characteristics that make it very attractive for the application under consideration, such as high efficiency (up to 98%), but at the cost of higher quiescent current (110μA in the best case).

Besides their relatively high quiescent current, their disadvantage is that they can only be operated as voltage inverters or voltage doublers, a fact that limits its possible uses. On the other hand, their definite voltage levels can also be seen as an advantage, for they simplify the certification for underground use. It is worth noting that efficiency increases with output current for inductive boost regulators, while it decreases for switched capacitive doublers. Therefore there is no simple answer to the question of which type is better, so the issue must be carefully considered on a case by case basis.

Regarding energy storage, two candidate technologies have been identified: Lithium based batteries and Ultracapacitors. Nickel based batteries are considered not appropriate due to their inherent quite high self discharging rate.

Each of the above technologies has advantages and disadvantages that as summarized in **Table 3.3.1-5**.

Comparison between energy storage technologies		
Technology	Advantages	Disadvantages
Batteries (Li Ion, Li Pol)	High energy density Fixed voltage levels while discharging	Certification issues (very high short circuit currents) Voltage fixed by battery chemistry
Ultracapacitors	Low self discharge Voltage level can be fixed by the user in a quite wide range	Lower energy density Some self discharge Voltage drops while discharging (dV/dt=i/C)

Table 3.3.1-5: Comparison between energy storage technologies

On the utilization side, the type of energy converter to be used depends on the voltage needs of the utilization circuit. If the voltage is higher than the one in the energy storage device, the same low Iq (quiescent current) switched regulators as mentioned above could be used.

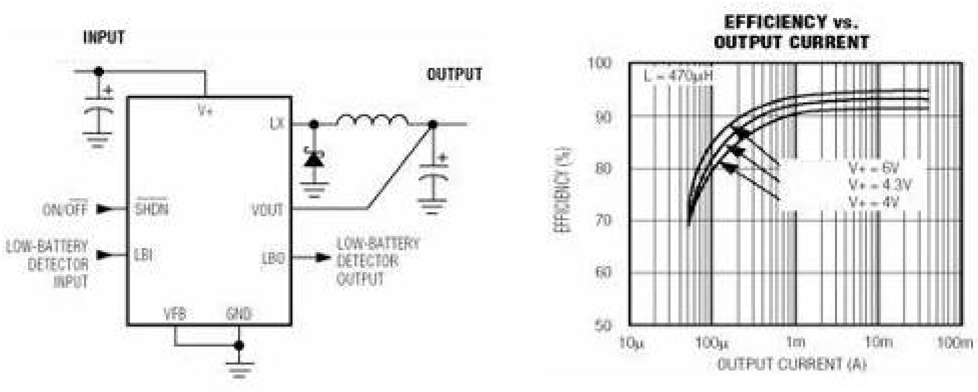


Figure 3.3.1-18: Inductive switched buck regulator: Circuit diagram and efficiency

On the other hand, if the storage device voltage is higher than the utilization circuit voltage two kinds of power conversion devices can be used, depending on the difference between them. If the difference is quite low, linear low dropout regulators (LDO) are the solution of choice. If the difference is higher, the so called “buck converters”, whose efficiency can be as high as 92%, with Iq = 10 µA are more appropriate.Typically LDOs will be used in conjunction with batteries, while switched converters will be used with ultracapacitors.

Power management for wireless m-Comm link

Developments in power management methodology are to be exploited by the wireless m-Comm link. For example, the power saving by employing low voltage devices (3V) and dc to dc voltage converters or power supply with nearing 90% efficiency nearly trebles the operational life from the same physical size battery pack. Further savings in power usage can be made by monitoring activity and automatically shutting down circuits when not required. Most Bluetooth, DECT, ZigBee and other wireless devices operate a wake-up mode for energy conservation, i.e., turning on the receiver intermittently to monitor for transmission activity. These power management methods have the ability of reducing average energy consumption to 1/100 of what it would have been. Operating on a lower voltage has an added advantage for the system to be certified intrinsically safe. The m-Comm wireless system would undoubtedly employ a battery pack of some kind as it power source. RMT undertook an analysis of available battery technology for the m-Comm wireless system, which included the characteristics of the key technologies. A discussion of these alternatives is given under Task 4.4 where the m-Comm development is described in more detail.

3.3.1.6 Examination of available operating systems for sensor networks (Activities Task 1.6)

Operating systems for wireless sensor network nodes typically are less complex than general-purpose operating systems both because of the special requirements of sensor network applications and because of the resource constraints in sensor network hardware platforms.

Wireless sensor network hardware is not different from traditional embedded systems and it is therefore possible to use embedded operating systems such as eCos or uC/OS for sensor networks. However, such operating systems are often designed with real-time properties, which typically are not needed in sensor networks. Operating systems specifically targeted at sensor networks therefore do not have real-time support. Four OS were selected as the most developed as follows:

Contiki is a small, open source, highly portable, multi-task computer operating system developed for use on a number of memory-constrained networked systems ranging from 8-bit computers to embedded systems on microcontrollers, including wireless sensor networks. Despite providing multitasking and a built-in TCP/IP stack, Contiki only requires a few kilobytes of code and a few hundred bytes of RAM. A fully fledged system complete with a graphical user interface requires about 30 kilobytes of RAM.

TinyOS is perhaps the first operating system specifically designed for wireless sensor networks. It is an open source component-based operating system and platform targeting wireless sensor networks. TinyOS is an embedded operating system written in the nesC programming language as a set of cooperating tasks and processes. It is designed to be able to incorporate rapid innovation as well as to operate within the severe memory constraints inherent in sensor networks. It is intended to be incorporated into smartdust. TinyOS applications are written in nesC, a dialect of the C programming language optimized for the memory limitations of sensor networks.

SOS is an embedded operating system written in standard C programming language, which has the ability to reconfigure individual components of a deployed system. It also has kernel support for common services such as dynamic memory allocation, simple garbage collection, and priority scheduling.The SOS Operating System provides:

- Enables heterogeneous system deployments.
- Easy program development.
- Truly modular system development. The modules that are used to create an application remain modular when deployed in the network.
- Debugging support via standard C code debuggers such as GDB.

Mantis is an embedded operating system written in vanilla ANSI C programming language, with no complex macros or language extensions to learn. The MANTIS Operating System (MOS) provides:

- A familiar, UNIX-like development and runtime environment
- A layered network stack that simplifies communication between nodes
- Support for multiple hardware platforms, including the MANTIS Nymph, the Berkley MICA2 MICA2DOT and MICAZ Motes, Moteiv's Telos RevB and x86 Linux
- Hardware driver system that abstracts the complexity of working in a with limited resources
- Debugging via a remote shell across a wireless link or wired serial connection
- Flexible power management features
- Dynamic reprogramming via wired and wireless connections
- Fast context switching (~200 uS)
- Round robin scheduling (MOS is not event-driven)
- A small memory footprint (can be as little as 500 bytes)

At the beginning of the project RAG examined the performance of prototype wireless sensors for temperature measurement from Rittal in the training mine (TBW). The data communication used Chirp technology (this kind of radio transmission is particularly interference-proof and economic with resources) using radio impulses in the nanosecond range. Following positive results, RAG decided to use the Rittal sensors in their further work. The operating system used by Rittal uses the Nanotron network software (Portable Protocol Stack). The smart wireless sensors of the company Rittal selected by RAG can only be acquired together with the Nanotron PPS. Because of the successful tests at the beginning of the project in the training mine, no further large investigations were undertaken by RAG on the topic of OS for sensor network.

3.3.2 Development of smart wireless sensor networks with innovative power supply strategies (Activities WP2)

3.3.2.1 Smart wireless sensors for temperature, humidity, pressure, flow-rate, rock stress (Activities Task 2.1)

In course of task T2.1 a number of laboratory and field tests (see **Figure 3.3.2-1**) have been carried employing various sensing techniques and low power wireless modules. These tests were aimed at finding best solutions for the integrated wireless sensor devices in terms of minimum power consumption, good measurement accuracy as well as flexible and robust communication schemes in underground conditions.

Figure 3.3.2-1 Various tests of sensor devices during development stage carried out in T2.1

As result the prototypes of wireless sensors were subsequently modified and improved to reach their mature form described in the following paragraphs. It is worth to mention that advantage has been taken of two complementary 2.4GHz ISM band wireless technologies: Chirp Spread Spectrum and ZigBee in order to enable vast scope of underground applications. First of the mentioned technologies offers unique multipath-resistant transmission capabilities whilst the second is well recognized standard with support for advanced multi-node mesh networking.

Chirp Spread Spectrum based wireless sensors

RAG worked with wireless sensors, which employ chirp modulation scheme for the transmission. The sensors operate with low power and the radio transmission used was found to be to high extent interference-proof. These wireless sensors operate in the following principle: a beacon signal is sent periodically and the measurement values are sent only when their change occurs. The wireless sensors and their necessary base stations (I/O Unit and Processing Unit) have been repeatedly improved. At the end of the project there were 4 different types of wireless sensors working with RF output power of 100mW available. It can be selected between wireless sensor modules for: temperature, humidity, proximity/access and digital input. Different tests were carried out in the training mine of RAG. The last tests were carried out with wireless sensors with 100mW power (details in the report of task 5.2).

The final test system consisted of the following components:

- 1 Wireless I/O Unit
- 1 Processing Unit II
- 1 Signal quality measuring sensor (with seven segment display)
- 2 Digital input sensors

- 2 Access (Proximity) sensors
- 2 Temperature sensors
- 2 Humidity sensors

Figure 3.3.2-2 I/O Unit and Processing Unit (left side), 8 wireless sensors (4 x 2 pieces) and on the top wireless signal quality measuring module (with seven segment display)

Technical details of the smart wireless sensors working with Chirp-Technology and compatible base station:

- ISM band 2.4 - 2.48 GHz
- Maximum data rate 2 Mbps
- Transmission power 100mW
- Supply voltage 3.6 V (Saft LSX 14500, Primary lithium battery, AA-size coiled cell)
- Standby power consumption 1.5 μA
- Battery service life up to 5 years

The electronic modules of wireless sensors (see **Figure 3.3.2-3**) are inserted in plastic housings. The housings have the following dimensions: length 90mm, height 30mm and depth 30mm. To interface with the sensors a base station – wireless I/O unit and processing unit were also developed. Both units are inserted in plastic housings (with metal face) of following dimensions: height 44.5mm, width 136mm and depth 129mm.

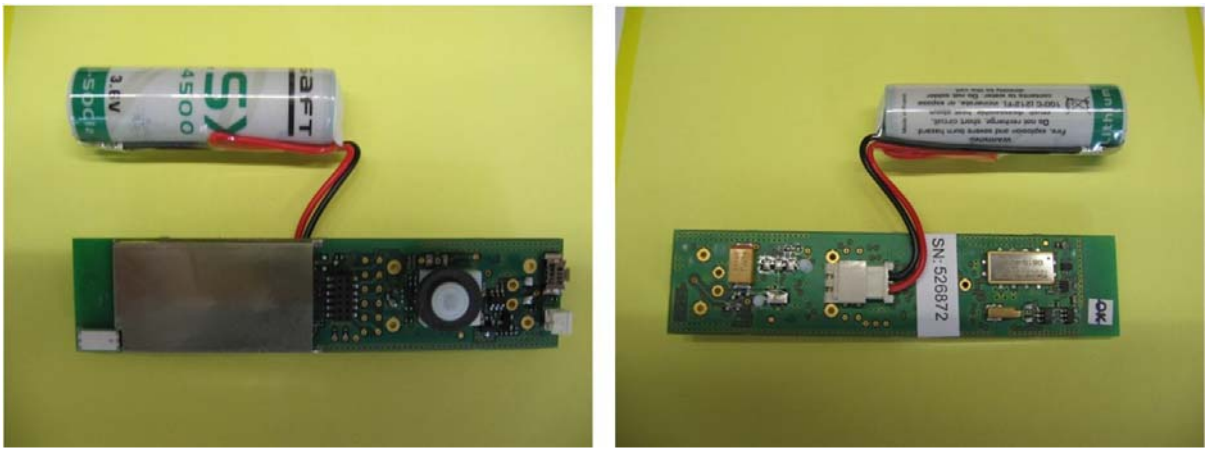


Figure 3.3.2-3 Wireless sensor modules with the battery (top and bottom side of PCB)

The I/O unit is the central component for the wireless sensors and must be connected with the processing unit. This can be made using Cat-5-cables (RJ45). Connection for both the data exchange and the power supply of the wireless I/O unit is done via the Cat-5-cable. Up to 4 I/O units can be attached to the processing unit. The I/O unit has an antenna fastened at the housing, which can be aligned according to the installation position. Optionally, this antenna can be replaced by an external one. Up to 4 I/O units can be administered with one processing unit and each of the I/O units can be connected to up to 16 wireless sensors. Thus in total up to 64 (4 x 16) wireless sensors can be operated with one processing unit. Using the processing unit the information from the wireless sensors can be processed and represented in the Ethernet over Web. At the configuration stage adding new sensors to the network is done manually in special learning mode with dedicated start-up buttons on the sensors and the I/O unit.

During the different tests carried out within task T2.1 in the training mine the following configuration was used (as shown in **Figure 3.3.2-4**): The I/O unit was connected with the processing unit via a Cat-5-cable. The notebook and the Processing Unit were connected with a switch. An alternative connection between notebook and Processing Unit was possible via a serial terminal interface cable.

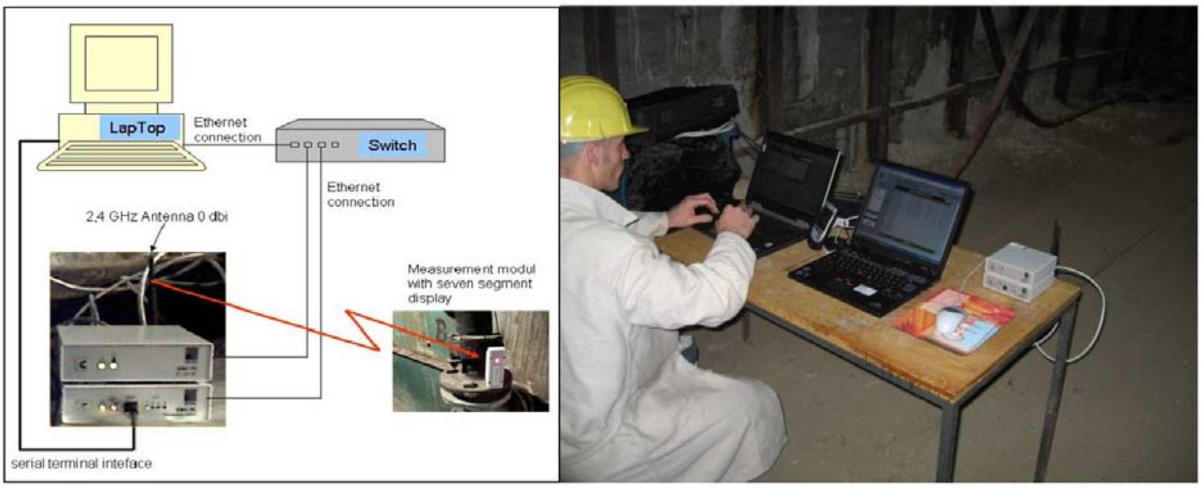


Figure 3.3.2-4 Configuration of a test set-up in the training mine of RAG

All measurements were displayed in the web browser of the notebook and in parallel also on a computer at the headquarters of RAG in Herne using dedicated software. The notebook had an Ethernet connection to a switch in the training mine and the training mine in Recklinghausen has a 20Mbps beam radio connection (point to point radio system) with the headquarters in Herne.

ZigBee based wireless sensors and actuators

1) ZigBee sensor node with versatile interfaces and DSP capabilities

A detailed functional specification was written for a whole family of wireless sensors, considering a common block, composed of the power supply, the wireless interface, and versatile sensor interface with connections for:

- temperature and Relative Humidity sensors
- standard Mine sensors with 0,4 ÷ 2 V output
- sensors with frequency output
- sensors with SPI digital interface

To handle computationally extensive tasks when required the devices are based on a DSP(Digital Signal Processing) capable microcontroller - Microchip dSPIC30F6014A or higher device, which is in charge of processing signal from the sensor and communicating with the wireless modem to manage the air interface. The **Figure 3.3.2-5** shows the block diagram of the device.Wireless interface used is based on an Ember ZigBee ETRX2 module, which is the evolution of the devices tested during initial stages of the project (ETRX1). The new version has been enhanced in aspects related to the power consumption and to the air interface.

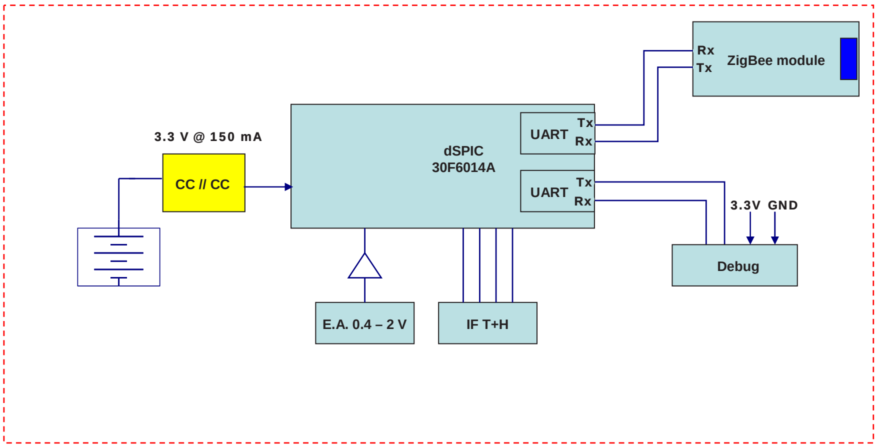


Figure 3.3.2-5: Block Diagram of the wireless sensor node

Based on the specification, prototypes of wireless devices have been designed and manufactured (see **Figure 3.3.2-6**). The device is capable to operate as RFD or FFD.

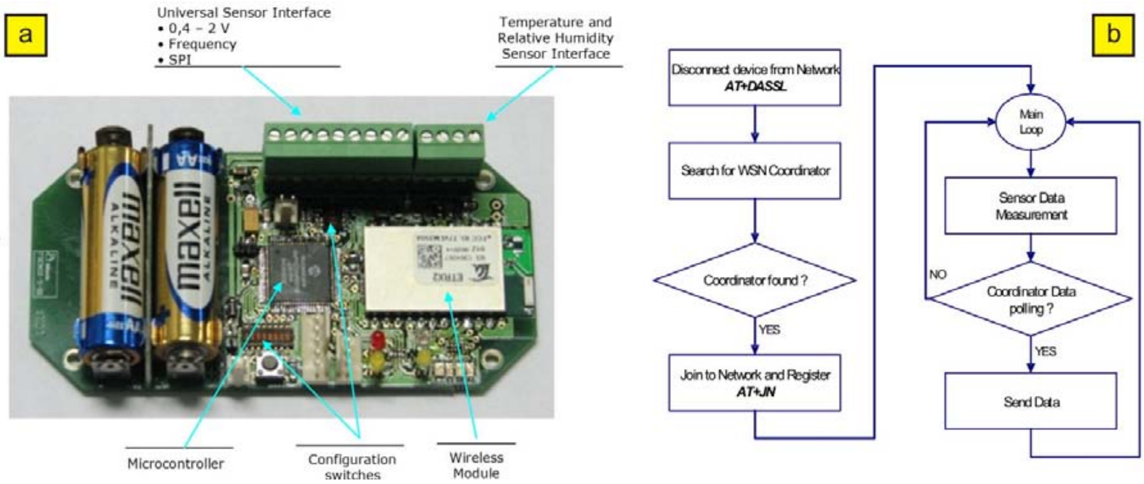


Figure 3.3.2-6 Wireless sensor prototype (a) control software flow chart (b)

First prototypes were Power by two AAA 1,5 V. In addition to this a connection for an external power supply is available, to be used in case that the internal battery is no powerful enough to supply the sensor connected to the device or alternative power supply. The prototypes were used in subsequent tasks and their functionality was successfully tested along the trials within WP5.

2) Ultra low power ZigBee Sensor Nodes for Environmental Parameters Measurement

Objective to achieve sensor devices of very low power consumption for measurement of environmental parameters was achieved in a few iterative steps. As result mature prototypes of sensor devices have been developed. Final revision of prototype sensors use unified chassis PCB which can be used in conjunction with differential pressure sensor, temperature& humidity sensor as well as communication interfaces (i.e. centrally powered modem or fieldbus interface). Crucial for low power operation was proper component selection and using advanced power management techniques.

The electronic circuit of the sensor node contains RF transceiver, ultra low power mixed signal MCU and dc/dc converter used to power the pressure transducer. The MCU contains multi-channel 12bit ADC and 12bit DAC. ADC inputs are routed to one of three expansion connectors. The remaining two have also GPIO (General Purpose Inputs/Outputs) and serial interface signals available. GPIOs are used to communicate with hybrid temperature& relative humidity sensor (see **Figure 3.3.2-7** (a)). Such an approach gives required level of flexibility to interface to build ‘virtually any’ analogue or digital sensor when necessary. In such case additional interfacing or signal conditioning circuitry can be connected on a add-on board plugged in to the expansion connectors.

In case of the differential pressure sensor (**Figure 3.3.2-7** (b)) the sensing element is connected to the MCU via I^2C interface. The device employs plug-in sensing element which can be used for measurement of differential pressure (25÷5000 mbar full scale) as well as barometric and absolute pressure (depending on used sensig element).

The developed sensors are intended to operate as end-devices (RFDs). They are powered from high capacity primary Lithium cell of low self-discharge current. The sensors are integrated with environmentally robust alloy enclosures with the sealed external +2dBi dipole antenna connected to the RF stage which operates at 0dBm output power. The devices have therefore reduced radio coverage but the advantage of low power consumption. Tests carried out in underground conditions positively proved communication and measurement performance of the prototypes.

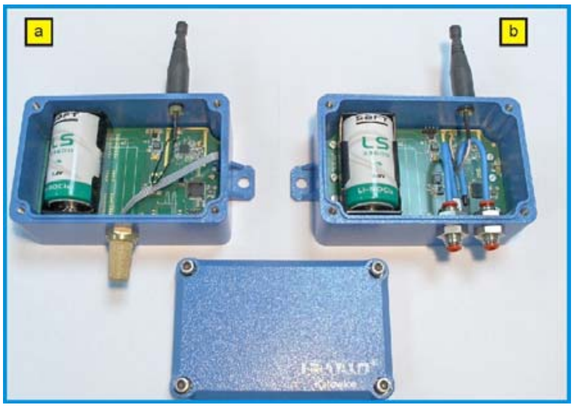


Figure 3.3.2-7 Final revision of temperature and humidity (a) and differential pressure (b) sensor prototypes

Manufactured sensors were used in the trials within WP5 for temperature, relative humidity and differential pressure measurements (see description of T5.1). The devices are highly optimised with regard to power consumption. The electronic units are characterised by very low standby current and the power saving modes of the ultra low power microcontroller are efficiently employed as well. It is estimated that at reasonable measurement duty cycle the battery life can reach up to approximately 5 years.

3) Machinery Control and Status Monitoring Wireless ZigBee Node

In addition to the monitoring applications, the use of ZigBee technology also allows to perform actuations over control systems. The use of these wireless devices for machinery controlling and status monitoring could have a great impact, especially in the case of mobile machines. A prototype device was developed based on the same Microchip microcontroller and ZigBee module architecture described earlier. It was named AES-WIZ and designed to be integrated with the mining machinery switchgear. It permits both monitoring the current consumption of the machines and controlling the power switch, providing a feedback to the control system about the machinery status as well.

Figure 3.3.2-8 Current sensor and interface relay based on ZigBee

In this case, the device takes the power directly from the gate end box where it is connected. The use of “ultracapacitors” as energy storage system allows the communication with the wireless network during 30 minutes without external power supply.

3.3.2.2 Alternative power supply for smart sensors and devices (Activities Task 2.2)

Within ***Task 1.5*** the basic physical key data to build up a practical energy-harvester were determined on the part of DMT with extensive measurements both at a real coal plough and at the corresponding conveyor. After further theoretical pre-considerations and mathematical calculations the final dimensions of the preproduction models for a single electro-magnetic energy-harvester were determined. Then manufacturing of the converter and corresponding test equipment was carried out. Blueprints of the devices and the manufactured prototypes are shown in the following illustrations.

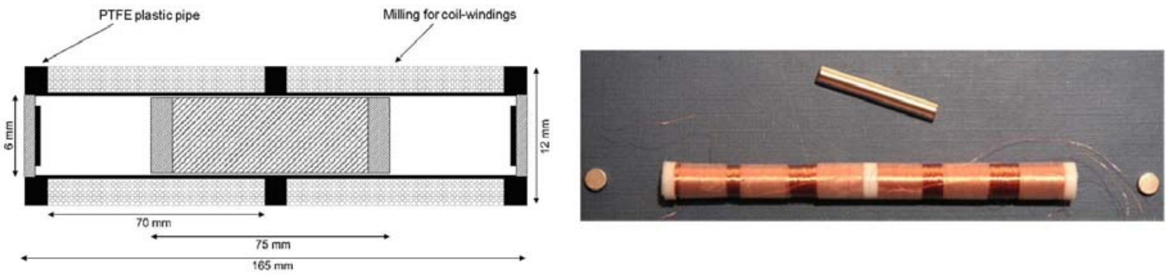


Figure 3.3.2-9 The sketch and the prototype of a single electro-magnetic energy harvester

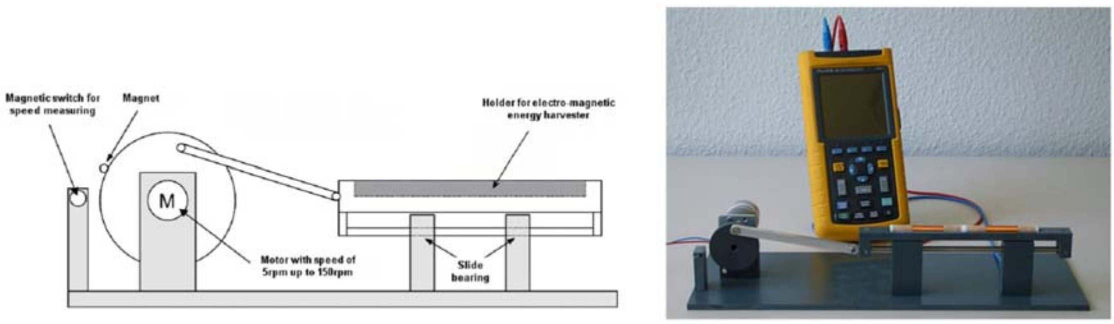


Figure 3.3.2-10 Rough draft and realization of a matching test-equipment

Comparison of the determined theoretical and the practical voltage, current and power values for the energy-harvester resulted in only a 3,8% deviation for the no-load case and 6,3% deviation in loaded state (at power adjustment). The theoretical calculated paremeters were as follow:

- current under load (at power adjustment): 0,529mA
- voltage under load: 274mV
- the resulting Power gain:145µW

Because practical results were achieved almost identical as theoretically calculated, in a further step (**Figure 3.3.2-11**) a practical copy of the transformer coils intended to multiply the induced voltage were manufactured. The circuit was formed by series-circuit of 10 double coils. After mounting of rectifier diodes, reservoir capacitors and protecting diodes this construction had to be encapsulated (for fixing and for mechanical protection of the only 100 µm thin copper-wires) within silicon potting compound.

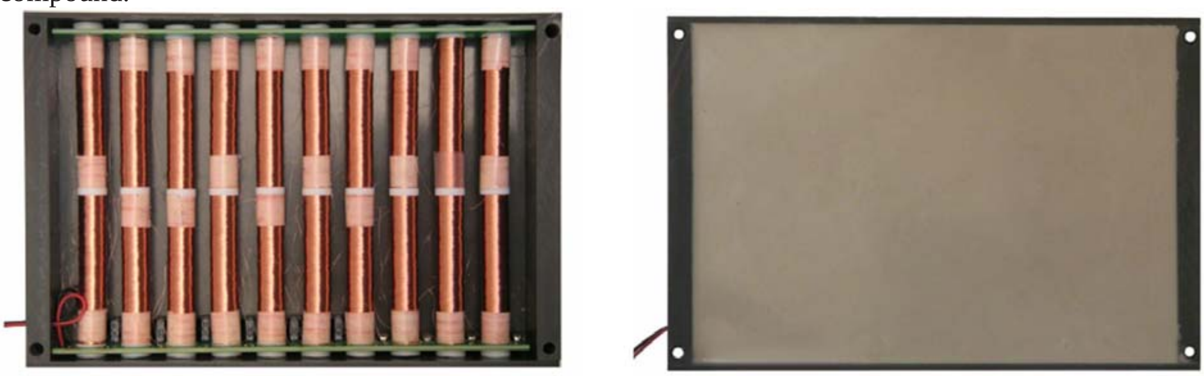


Figure 3.3.2-11 10 times 2 one behind the other switched energy-converters of Figure 3.3.2-9

Unfortunately, the series-circuit of the 10 times 2 transformer coils did not bring simultaneously a 20-

times bigger (20 times 145µW = 3mW) energy output in turn.
This problem was presumed in first as a consequence of the mutual influence of the extremely strong magnets within the small coil tubes, what could be confirmed then by a percentage improvement with outflows of every second tube. Nevertheless the values were left around half an order of magnitude behind the expected values so that only a moderate success could be booked here. Furthermore the handling of the filigree wounded copper wires is extremely problematic because if only one of these connections breaks, the whole device which is based on series-circuit of 20 reactance coils - will become useless and can furthermore never be repaired after being encapsulated into the potting compound. Therefore, proper encapsulants and handling technology should be used to reduce the risk otherwise such a concept can become uneconomical from the mentioned grounds.
Nevertheless the developed concept should not remain unused (in spite of the limited harvested energy amount) and was employed therefore for the development of an energy supply, where the power gained from the swinging-system could serve for re-buffering of three 1,25V ENELOOP rechargeable batteries with extremely small loss of spontaneous discharge. This buffering scheme enables a sufficient energy source for approx. 3 years maintenance-free operation of sensor devices under the asssumption that the supply system is loaded with an extremely power-efficient circuit, where only temporary (for example once every 10 minutes) measuring cycles and subsequent wired or wireless data communication should be carried out. (An example of such an application is the radio-sensor for rock stress measurement (see ***Task 3.3***).

During the RAINOW-project similar vigour results with similar energy generation systems were determined by the project-partners involved that indeed sufficed for simple temperature acquirements, not however for the recording and transfer of DMS signals (abbr. <u>D</u>ehnungs <u>M</u>ess <u>S</u>treifen - strain gauge) on mobile machines and/or machine parts as initially planned.

3.3.2.3 Interface connectors and electronic control units (Activities Task 2.3)

In the strongly branched underground networks the previous bus systems (like RS485, POFIBUS etc.) with their large technical expenditure are replaced in current days by much more effective ETHERNET-based bus systems. The communication equipment used for that purpose takes advantage of well proven industrial solutions properly modified for operation in conditions of underground mining. Next to the high performance ETHERNET networks using data transfer via optical fibre (mostly used for back-bone management just like "data-highways") also the radio-based Wireless LAN networks have found their way to underground.

There are however a number of useful interfaces and interconnection equipment to input devices such for example the novel sensor networks not implemented in contemporary mining FO-based LAN /WLAN systems. For that reason the appropriate "net-nodes" had to be developed taking into account fulfilment of all the necessary requirements for underground use.

In the frame of this project and especially in task T2.3, DMT had decided to develop a dedicated to mining use “net-node” or “Multi-switch”, which covers both, the connection for the still used old galvanic separated TTY-interfaces and (that is new) also for the copper-based ETHERNET-interface via RJ45- connector. In a preceding RFCS-Project (RFC-CR-03003) this interface was certified for underground use under the restrictions of ATEX directive for the first time. The interface operates with galvanic separation at 100 Mbps data throughput over a range up to 40m.

In a very first step of development a market research was carried out in order to find the necessary and available networking components such as Wireless LAN access-points, ETHERNET-switches and RJ45 to optical fibre media-converters. In case of the ETHENET to TTY converter advantage was taken of the solution developed under the already mentioned preceding RFCS-project.

In the next step selected different media converters for single mode fibre lines were analysed and evaluated concerning their aptitude, their price/performance ratio and their power consumption. In the same way also different WLAN access-points were tested with regard to their radio coverage, data transfer rate and immunity to faults. Also performance of various passive aerials was examined by measuring and recording the field strengths for different environmental conditions.

During the course of this project the demands for the conclusive application changed several times, especially for the use and requirements concerning the ETHERNET-fibre connectivity.

Feedback from cooperating mining stuff indicated the developed device should also be able to operate as a “net-node” within an uninterruptible fibre-backbone-network based of ring topology. Therefore, these requirements were taken into consideration and the concept for final device was reworked. The logical schematic of the new design for the Switch is shown in the **Figure 3.3.2-12**.

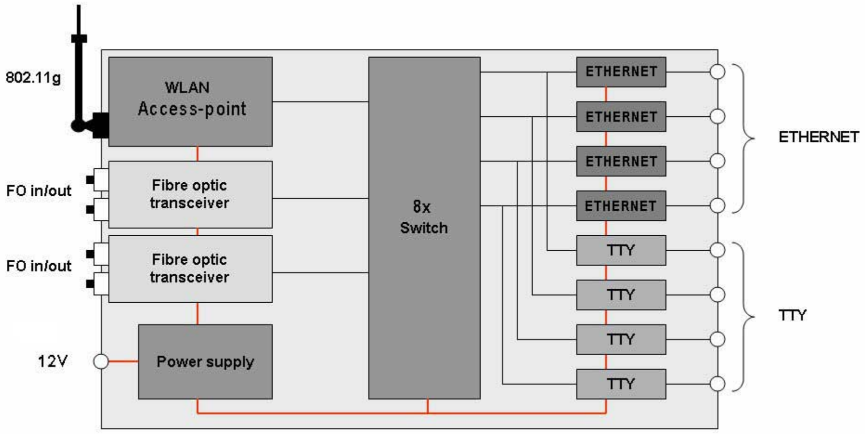


Figure 3.3.2-12 **The schematic of the final “Multi-Switch”**

Additionally to already possible two bi-directional communication interfaces via optical fibre application of an access point extended the initial functionality of a “Multi-switch” in a considerable way. Therefore the “Switch” was renamed to **D**ata-**A**cquisition-**G**ateway (short “DAG1“. This should guarantee the device functionality as data-collector and/or data-distributor with linkage possibility (*here Gateway*) to the plant-backbones.

In a next step the modular concept was extended once again to accommodate now up to 5 optical ETHERNET-transceivers, up to 4 intrinsically safe RJ-45 interfaces and up to 6 TTY (20mA current loop) interfaces. The choice between copper ETHERNET (via RJ45 plug) and the current-loop (TTY) interfaces will be carried out manually by means of mechanical switches. Any combination between TTY and ETHERNET-connections will be possible. Due to the implemented access point this device will be able to serve further 253 participants next to the described ones. To offer an economical device with flexible connectivity all represented interface modules can be either implemented or skipped depending on demands.

Specific features:

- The DAG1 is tailored especially for underground applications, however it can also be used in industrial surface applications.
- The access point with five different operation modes can also contribute to the enlargement of the superordinate network-infrastructure. The device can operate in access point mode, wireless-client mode as well as in the repeater mode which offers furthermore the possibility to combine different nets via the bridge-functions "AP-to-AP bridge" and "AP-to-Multipoint bridge" with each other.
- The entire electronic of the DAG1 is put in a high-grade steel case built with 2mm thick walls, with corresponding cable glands for the individual interface wedges and/or couplers (*for optical fibre OF*).
- The device contains not Ex-certified industrial components and therefore a temperature-resistant and gas-proof potting compound is necessary, all connections of the interfaces to the ‘outside’ are intrinsically safe. This was accomplished by employing opto-isolated TTY-interfaces as well as via the natural decollating-media “air” (*at WLAN*) and “glass” (*at the OF link-up*). In the case of the copper based ETHERNET-interfaces the intrinsically safe isolations are achieved by certified inductive separations in the communication path.
- The device features also status indication by means of LEDs installed behind the glass pane within the casing cover – they indicate power supply status and physical connection status of the individual communication interfaces,
- The control elements of the DAG1 were positioned for the purpose to minimise possible operating errors in the interior of the device. Several mechanical changeover switches can be

used to determine between the user interfaces of TTY and/or copper-ETHERNET.

Development, Certification and Tests:
During the project the development of the DAG1 had to be repeatedly reengineered (as it was described in earlier paragraphs) because of that the certification work was delayed slightly comparing to original plan. Nevertheless, the certification was finished successfully within project running time, approved with the commitments of Ex I M2 Ex ib I and registered under: **BVS 08 ATEX E 219 X**

Further performance tests of the DAG1 were carried out repeatedly with different preproduction model during laboratory experiments at DMT and in the training mine of the RAG in Recklinghausen (see ***Task 5.2*** description).

Design of the DAG1:

In the final revision of the DAG1 next to the four optionally usable TTY and copper-Ethernet cable glands (in the middle) also those for the power supply (to the left) and the two cable glands for the optical fibre lines (at the right side) were located at the bottom of the enclosure.

The pictures in **Figure 3.3.2-13** show the modular version of preproduction models used for the tests.

Figure 3.3.2-13 Pictures of the DAG1-prototypes

ZigBee to Fieldbus Gateway

Based on the functional specification referred in Task 2.1, a ZigBee gateway has been developed, working as a Coordinator in a WSN, performing functions like the establishment of the wireless network and the gathering of data from all the sensors connected to its network. The picture below shows the block diagram and the printed circuit board of the unit.

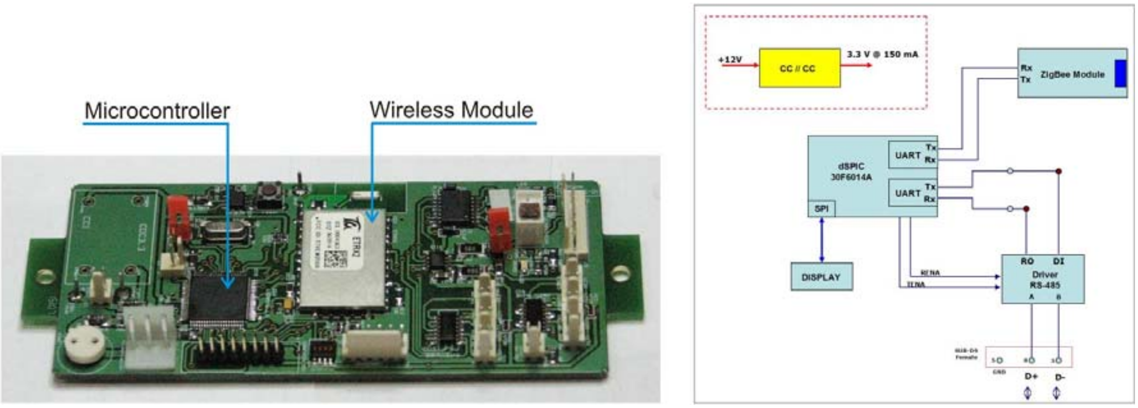


Figure 3.3.2-14 PCB and block diagram of Zigbee to Fieldbus Gateway

The interface of the gateway with an external system is done by means of an on-board differential RS485 driver, which allows the direct connection of the device to the Field Bus control and monitoring system commonly used in the Spanish coal mines. The interface is specifically designed to be compatible with other designs developed under other RFCS projects (for further details, consult RFC-CR-03003: Enhancing the performance of mine communication, warning and condition monitoring systems; 7220-PR/133: Extending the utility of underground data transmission networks and other data processing equipment). Communication with any other physical interface (WLAN; Ethernet, etc.) would be possible using media and / or protocol converters.

The gateway is based on same microcontroller and wireless module as those used in the wireless sensor node (see description of T2.1). The the ZigBee module is in the option with an embedded chip antenna. For the first prototype, the electronics was inserted in a plastic enclosure, which made possible the use of a chip antenna. The prototype device was used as sink node operating in conjunction with mining SCADA software in course of field trials carried out in WP5 (see the WP3 description).

ZigBee Gateway for centrally powered systems

To fulfil requirements of intrinsically safe communication systems with central power supply which are commonly used in Polish coal mines a modified version of Zigbee gateway was developed (see **Figure 3.3.2-15**). The device in final stage was built based on the hardware solution (the same PCB and electronic modules), which was developed for wireless sensor nodes described in T2.1. The main difference is presence of centrally powered V.34 modem with phantom power supply type. Because of this no separate power supply is required which results in reduced purchase and maintenance cost.

It is possible to use it as M1 device operating in hazardous areas of mine (powered via intrinsically safe barrier). This feature is especially convenient for deployment of continuously operating monitoring networks. The device is intended to operate in conjunction with ZIST/µZIST multiplexing systems (by EMAG), but can also be connected to any standard telecommunication system with central power supply fed through safety barriers.

Figure 3.3.2-15 ***Centrally powered Zigbee Gateway; (a) – dimensions (b)view of the unit with removed cover***

The prototype of centrally powered ZigBee Gateway was used extensively during the underground field trials carried out in Guido mine. The modem connection enabled successful communication with the data acquisition software running on the surface.

Principle of Operation of the Control Software for ZigBee Gateways

Dedicated control software has been developed for both versions of Zigbee Gateways which enabled basic data acquisition and management tasks. The devices are operating as network sink nodes which collect data from distributed wireless sensors. The developed devices were programmed as the coordinator nodes of the WSN and are responsible for establishment of the network and the gathering of data from all the sensors connected to the wireless network. Microcontrollers of the ZigBee gateways are responsible to configure the wireless communication interfaces (i.e. wireless module or transceiver chip) and cable modem (in case of centrally powered revision). After this action the ZigBee wireless network has to be established. Once the network is established, the coordinator searches for the sensors located in the coverage range and connected, and then gathers the data (identification, address, type of nodes, etc.). Once the network is establishes and all the relevant data are collected, the coordinator starts to poll each node periodically in order to collect the measured parameters (see **Figure 3.3.2-16**).

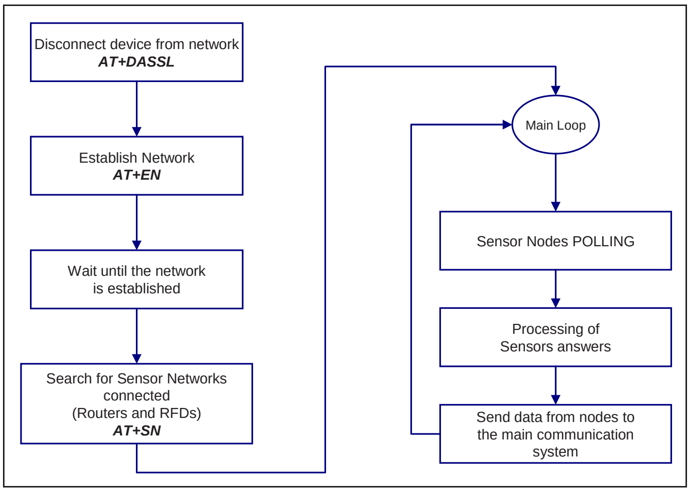


Figure 3.3.2-16 ***ZigBee Gateway Software Flow Chart (AT commands for the wireless module in bold)***

3.3.2.4 Development of mobile and stationary intrinsically safe RFID-read and -write equipment (Activities Task 2.4)

An extensive appraisal was undertaken regarding the potential benefits and application issues associated with adopting LR-WPAN (low rate wireless personnel area network), e.g. Zigbee / IEEE 802.15.4, type wireless devices as an alternative or supplementary technology to conventional mining RFID schemes. A comparative assessment with state of the art ATEX-certified RFID technology confirmed that significant simplification and cost saving should be possible. RFID schemes require relatively complex RFID readers and associated RFID antennae. Even where RFID readers are designed to provide multiplexed reading with several read antennae, there was still anticipated to be inherent cost and technical advantages in using LR-WPAN wireless devices. Looking forward to future application, it is projected that systems using both RFID and wireless network devices respectively will find application in mining, with perhaps RFID systems continuing to be used in safety-critical applications, where there is significant experience and confidence in the use of these systems. The facility to simplify and lower costs of reading points in low rate wireless personnel area network based tracking systems confirms that this is likely to become the primary technology for emergency location, tracking and deployment monitoring applications. Further comparison between RFID and LR-WPAN is given below.

Tracking in underground mining has commonly been achieved in recent years through the use of active or passive RFID (radio frequency identification devices, otherwise known as 'Tags', or 'Transponders'). There are a number of systems available in the market ranging from tags that simply record whether personnel have entered the mine, to providing more locational awareness of personnel whereabouts. RFID in general, is finding use in a wide range of applications. **Table 3.3.2-1**, shows the different types of RFID technologies relating to operating frequency, active or passive, and some examples of application (IET, 2006).

Band (MHz)	Typical Range		Typical Tag Size		Relative Data Transfer Rate	Typical Applications
	Read Only	Read / Write	Active[2] (cm^3)	Passive[2] (cm^2)		
0.125 – 0.134	> 2m	Few cm	5–10 cm^3	2–5 cm^2	Slow Non-concurrent multiple access	Animal ID Car immobiliser Access and security
13.56	> 1m	> 0.5m	3–5 cm^3	10 cm^2	Medium Multiple concurrent read <50 items	Smart Cards Smart labels Domestic electrical goods Access and security
433	Tens m	Few m		5 cm^2	Active tags	Specialist Animal Tracking
860 – 960	> 5m	> 0.5m	1–2 cm^3	4 cm^2	Fast Multiple concurrent read >100 items	Asset tracking in industrial and consumer distribution
2450	> 10m	> 1m		1 cm^2	Fast	Moving car electronic toll collection

Table 3.3.2-1: RFID Technology Characteristics

There are a number of characteristics to consider regarding the type of RFID system to develop or use in an application. Depending on the nature of these, it can lead to complex design issues in the reader or interrogator unit. Summarised features of RFID based tracking are individually listed below:

Advantages of RFID tag based tracking:

- Simplified robust design from the tag (or transponder) perspective.
- Tags require minimal, or no battery power.
- Ease of installation and maintenance – requires minimal user input, easily scalable, and easily replaced.
- Each tag can be made completely unique.

Disadvantages of RFID tag based tracking:

- The interrogator or reader might need to be very complicated; particularly if multiple tags are needed, and certain parameters are not constant e.g. tag orientation, speed, range etc. This will ultimately lead to relatively expensive reader units.

An example of a state of the art active RFID tag system (Minewatch) developed by Davis Derby for mining is shown below in **Figure 3.3.2-17**. The diagram shows the general requirements of a mine tracking system. This system has similar advantages and disadvantages to those described above. In addition to potential cost saving, another key advantage of employing a wireless networking technology, e.g. LR-WPAN, to achieve underground positioning/tracking, is additional functionality. An example of a related technology is the WiFi based active RFID tracking system for underground mines which Mine Site Technologies and Aeroscout (www.aeroscout.com) have developed. This system offers standard WiFi services along with the ability to track mobile nodes travelling around the mine. There are of course disadvantages with such a system, such as the battery power required on mobile units, and more complicated software and network protocol design.

Wireless technologies with mesh capabilities, such as LR-WPAN and others, were of particular interest within this research project. The mesh networking characteristics, such as the ability to self-heal, self-organise, provide redundant pathways etc, allow for significantly increased network robustness. As part

[2] Active tag size given in volumetric dimensions, passive is described in terms of area only as passive tags are generally made virtually flat <1mm in height (IET, 2006)

of this, mesh networking stack options e.g. EmberNet and EmberZNet, were evaluated under WP1. Factors including dynamic vs. static networks are crucial factors in the design of such systems.

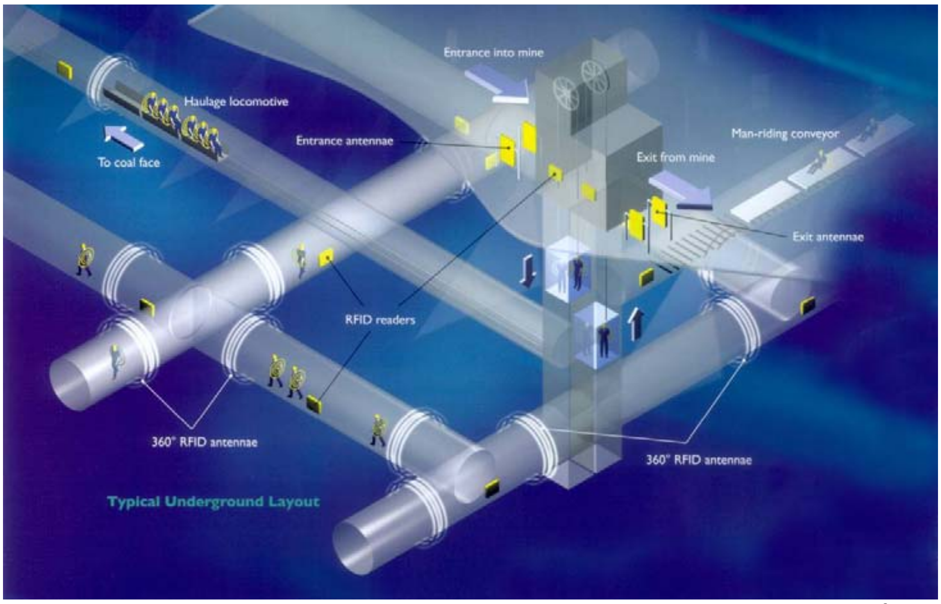


Image courtesy of Davis Derby, UK

Figure 3.3.2-17 Mine RFID System and Requirements

Zonal Location Tracking

Software was developed and refined software for zonal location tracking using EM2420 mesh wireless networking devices and the EmberNet mesh networking stack. The feasibility of the underlying concepts here was confirmed under the previous ECSC 7220 PR-133 project. The application shown in **Figure 3.3.2-18**, demonstrates a method of using ‘beaconing’ to track a mobile device. The full-functional devices (FFD) are set up in pre-determined locations. The FFDs then periodically transmit beacons. The reduced functionality RFD, or ‘leaf-node’ (EmberNet specific term) devices then pair themselves with a particular FFD upon receiving a beacon. The mobile node is then actively ‘tracked’ both entering and leaving a ‘zone’. The disadvantage of incorporating beacons is that they are sent separately to the MAC layers CDMA/CA, and that careful design is required to ensure efficient use of network resources. The work reported here contributed to other project tasks, specifically T3.4 and T4.6, where significant further work into underground tracking using wireless technology was conducted.

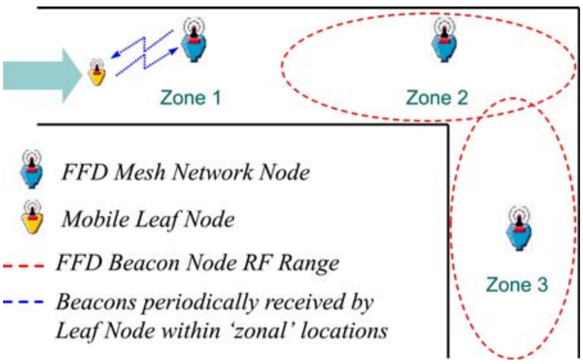


Figure 3.3.2-18 Example of zonal location information from EM2420 devices and ‘beaconing’

Innovative dual band active RFID equipment

At the end of the project there were ATEX approval-eligible active transponders (5 units +1) and the required transmitting / receiving stations (2 units) available. The active transponders and their transmitting / receiving stations (base stations) were repeatedly improved during the project period. RAG carried out different tests with active transponders and their base stations under operating conditions in the training mine (the last tests are reported in work package 5 (WP05), in task 5.2). For arousing the active transponders very low frequencies are used, because they are very advantageous related to avoidance of "dead spots" and range curtailing due to the presence of metal structures. Such transponders have three antennas, which are arranged in x, y and z-direction. The transmitting part of the transponder is a conventional UHF transmitter. The use of a higher frequency band in the transmitter allows higher data rates which are necessary for reasonably high read rates. The block diagram (see **Figure 3.3.2-19**) presents the principle structure of the active transponders.

Figure 3.3.2-19 Prototypes of active transponders – first and last models. And the principle structure

The prototypes of the active transponders were significantly reduced in size during the run time of the project. The size of the housing now essentially depends on the size of the battery used. The new prototype housings have the following dimensions: length 70mm, width 50mm and height 24mm (if the mounting area is included, the housing has the following dimensions: length 70mm, width 70mm and height 32mm). With the lithium batteries now fitted (LS14250, 3.6V) a service life of up to 8 years was calculated. If a button cell battery (CR2430) is used, a service life of 2 to 3 years is expected.

Figure 3.3.2-20 Active transponder with a trade standard 3V lithium button cell battery CR2430

The board of the active transponder, including the button cell battery, has the following dimensions: length approx. 41mm, width approx. 32mm and height approx. 9.3mm (see **Figure 3.3.2-20**). A 3D antenna is utilised in the transponder for field strength detection. This antenna is connected via an analogue switch, which is controlled by a microprocessor, to an AF receiver. The three reception channels are cyclically connected to the receiver. For determining whether a transmitted signal is present, and in which channel the currently best signal is available, an RSSI assessment is first of all made (RSSI "Received Signal Strength Indication" is an indication for the reception field strength in wireless communication applications). Each channel is connected for about 1.7 ms to the AF receiver and thereafter the RSSI voltage is measured. The RSSI measurement cycle consists of the sampling of all 3 reception channels. To ensure that the call field strength threshold is the same in all orientations of the transponder, a vector is calculated from the RSSI values of the individual channels. If the vector RSSI exceeds the vector threshold value, the microprocessor evaluates the present signal with its operating software, with regard to the signal validity, i.e. it demodulates the magnetic field. In the case of a positive demodulation result the transponder knows by which procedure it must then assemble its return message information. It transmits via the UHF transmitter back to the reading station its own ID, the magnetic field ID and further device parameters. The transponder ID is a 16 bit address, i.e. it is possible to distinguish between more than 65000 transponders. This ID can be modified by parameter setting, via the magnetic field. Furthermore, the transponder has a fixed set device code that is also transmitted within the UHF return transmission. To permit battery life evaluation in future, the status of the battery is also transmitted. With regard to the communication between the active transponder and the transmitting / receiving station, further improvements were implemented at the end of the project: In addition to the UHF transmitter, the active transponders now also have UHF receivers. When they have been detected within the 9 kHz magnetic field, they can be switched off specifically by the transceiver station, which can significantly extend the service life of the battery. The number of detections will be substantially increased by this procedure. The arousing frequency continues to be 9 kHz, the communication frequency can be parameterised: 433 MHz or 868 MHz. The transponder has an integrated movement sensor, which makes a further reduction in the actual power consumption possible. This is achieved by the way that it checks for the presence of a 9 khz field quite often when it is moving, but much less frequently when it is not moving.

Figure 3.3.2-21 Transmitting / receiving station (base station) with closed and opened housing

The base station includes a media converter from copper to fibre optic. In the left picture (**Figure 3.3.2-21**) the base station with the closed housing is shown: on the left side is the UHF antenna (black) connected, on the right of the housing the both E2000 fibre optic connectors green and red with orange wires, golden with black wire the power supply and for the loop antenna the two red wires. For the loop antenna is now only a simple wire sufficient (successful tests were made with the highly flexible red wire (LiFY) with cross section of 0,50mm, see WP 5). The picture on the right side shows the base station with opened housing, the media converter is located behind/under the transmitting / receiving circuit board. The complete hardware of the base station is integrated on one small board (without the media converter). This board has the following dimensions: 160 mm x 90 mm (see **Figure 3.3.2-22**).

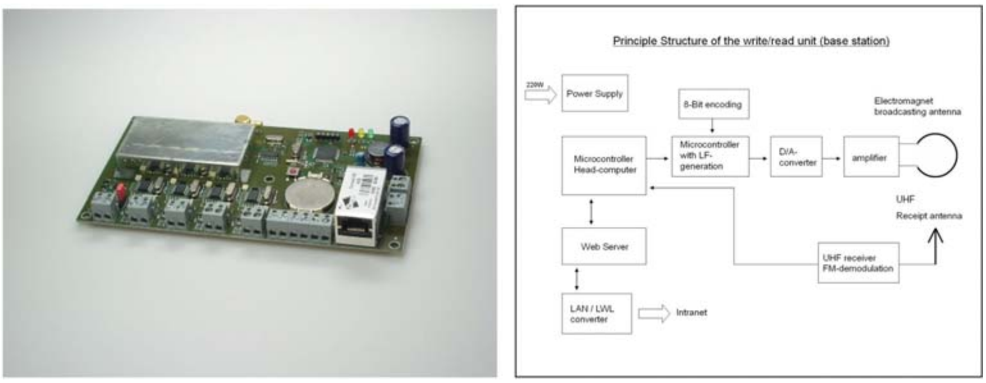


Figure 3.3.2-22 Complete transmitting / receiving station (PCB) and the principle structure

A sinusoidal carrier frequency of 8.3 kHz is generated with a micro-controller and a D/A converter. The carrier frequency is frequency-modulated with a deviation of ± 700 Hz by the information that is to be transmitted. The transmission rate of the data stream must be significantly smaller than the carrier frequency. A modulation frequency of about 165 Hz is chosen. Because of the low transmission frequency, the number of data bits of the magnetic field information must be small, to keep the necessary time for which a transponder is in the magnetic field as short as possible. Therefore the data stream consists of only 12 bits. 4 bits are used for the status message and 8 bits for the field designation. This allows 256 distinguishable magnetic field values. With the 4 status bits, 16 different control commands can be sent to the transponder. Therewith it is possible, for example, to communicate system parameters, such as functional principles or service settings, to the transponder via the magnetic field. The very low frequency signal for generating the encoded magnetic field is fed via an AF bridge amplifier to a loop antenna, and a potentiometer is provided as a control element for setting the magnitude of the magnetic field. The return message from the transponder is picked up by a UHF receiver. The transponder designation and the associated system data are at present transferred to the system computer via fibre optic cable with TCP/IP (Ethernet). The receiver output generally consists of 8 bytes having the format 19200-8-N-1. The data are forwarded as follows: Transponder ID high byte, Transponder ID low byte, Magnetic field ID, System code, Telegram type, Data 1, Data 2 and Data 3. The software of the UHF receiver checks continually for the presence of a radio signal. With a single base station, up to 4 magnetic fields (9 kHz) can be generated. This may be useful in mining underground in the area of junctions and crossroads; furthermore, using two magnetic fields arranged one behind another, a direction can be determined in important areas underground.

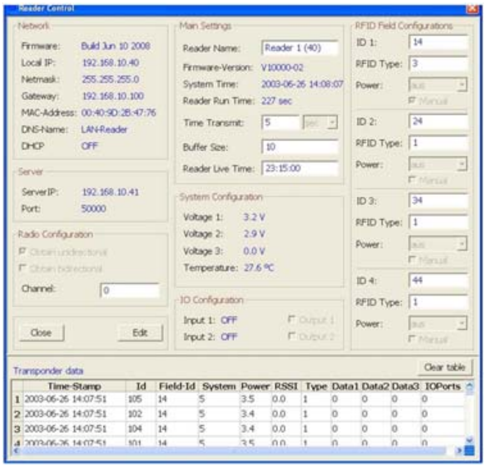


Figure 3.3.2-23 Screenshot of the visualization of the Transponders on a computer display

A mobile RFID read and write equipment was developed for reading out the active transponders without the stationary base stations. With this equipment it is possible to use a pocket PC for diagnostic purposes. The mobile RFID read and write equipment has an overall length of about 230 mm housing on the left and antenna assembly on the right) with a housing size of about 150 mm*40 mm*32 mm, an antenna diameter of about 15 mm and an antenna length of about 80 mm. The housing accommodates the rechargeable battery (marked blue) and the main board (marked green); an ON / OFF pushbutton and an LED for indicating the operation of the system are provided on the outer side of the housing (on top in the drawing).

Also the charge socket for the battery, a bluetooth LED and a bluetooth pushbutton (shown on the bottom in the **Figure 3.3.2-24**) are arranged on the outer side. The mobile RFID read and write equipment is switched on by using the ON pushbutton and the bluetooth pushbutton serves to build up a bluetooth connection with the pocket PC. Further RFID read or RFID write operations are performed with a special software program installed on the pocket PC. The pocket PC is of an i.roc type which has been used by RAG already earlier. The communication path is as follows: RFID transponder <-> mobile RFID read and write equipment <-> pocket PC.

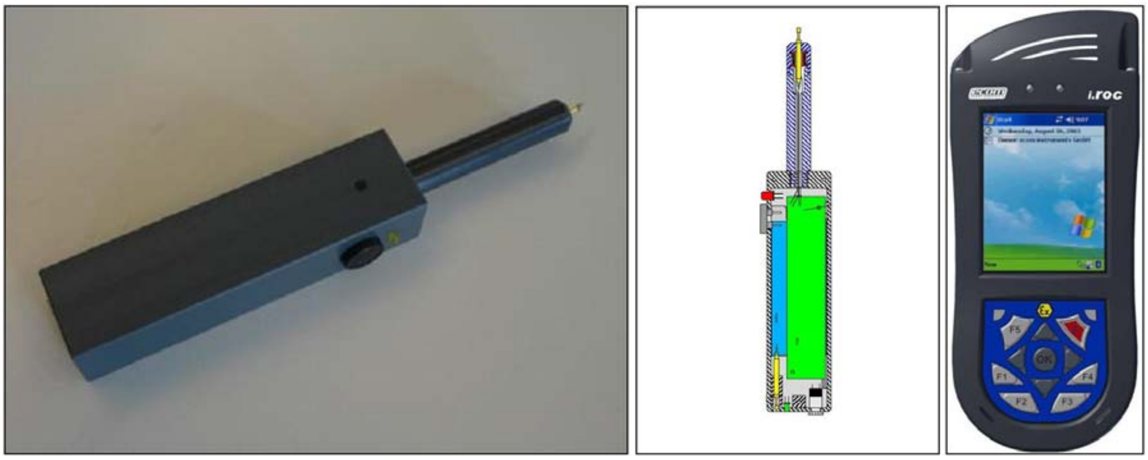


Figure 3.3.2-24 Picture / drawing of the mobile RFID read and write equipment, and pocket PC

3.3.3 Development of applications for the utilisation of smart wireless sensor networks (Activities WP3)

3.3.3.1 Temperature monitoring in the area of conveyor belt drives with sensor networks (Activities Task 3.1)

Initial work in this WP concerned the scoping of requirements and limitations of current mine practices. Despite widespread use of point carbon monoxide (CO) and smoke sensors underground, there continues to be a significant number of conveyor fire incidents recorded where fires are either not detected in their incipient stage, or, detection sensitivity and low specificity leads to an unacceptable number of false alarm incidents. These frictional fires can originate at both the conveyor drive head and where conveyor rollers have become seized. Initial studies confirmed that both carbon monoxide electrochemical cells and semiconductor smoke detectors have fundamental limitations. In many frictional conveyor fires for example, carbon monoxide levels can remain very low until a late stage of combustion. Whilst this class of fire can produce noticeable smoke, which may be detected by semiconductor products of combustion sensors, the inherent lack of specificity of these sensors leads to false alarm triggering from sources that include diesel vehicle emissions and explosive fumes. The spacing of detectors may also be sub-optimal. Work was directed within RAINOW towards two avenues:

1. Determining what class of fire sensor and the sensor location and spacing is most appropriate to address conveyor belt fire risk assessments, and

2. Identifying what form of wireless transmission scheme is relevant to support, possibly, a chain of sensors located along a conveyor belt drive.

It was acknowledged that conveyor roller fires present a difficult detection problem in that adequate sensitivity and localisation of the fire point of origin potentially requires a relatively large number of sensors. One option might be to engineer very simple temperature-triggered wireless sensors which are disposed at regular intervals along the conveyor structure. Ultimately, if engineered to be sufficiently small and fit for purpose, these units could be bonded to the idler bearing carriage close to the roller (or even within the roller bearing shroud). These simple temperature-switched sensors could be engineered to consume negligible power until activated. The other option would be to select fire specific sensor types which provide a secure, discriminating response capability to a wide variety of incipient mine fire types. This would involve combinatorial sensing approaches to carbon monoxide and other physico-chemically active species within products of combustion. An additional sensing capability to account for characteristic levels of nitrogen oxides would also be needed as a compensation input. These units would be located at somewhat larger intervals along the conveyor line and could communicate by wireless means. A power supply would however have to be provided locally for these continuously active fire sensors, which is a disadvantage.

Since the **Tasks 3.1** and **3.2** complement one another the application-development of MRSL for temperature monitoring, environmental monitoring, remote machinery telemetry and diagnostics can be found in the next **Task 3.2**.

In January 2007 measurements with thermo-graphic equipment were carried out by EMAG in coal mine Chwalowice (Rybnik). The measurements were intended to collect information regarding thermal behaviour of selected components of belt conveyor. Particularly the observations of temperature distribution within area of drive pulley drums and idlers were carried out. It was found that with the thermal imaging equipment normal operation and pre-failure conditions could be easily observed.

As result of that research it was found that abnormal conditions at the idlers (see **Figure 3.3.3-1 a,b**) can be easily detected by measuring the difference between the ambient temperature and the temperature of the frame. The temperature sensors should be located at the bracket as close to the axle as possible. Such an approach is the alternative to scheme with simple miniature temperature sensors integrated with each roll.

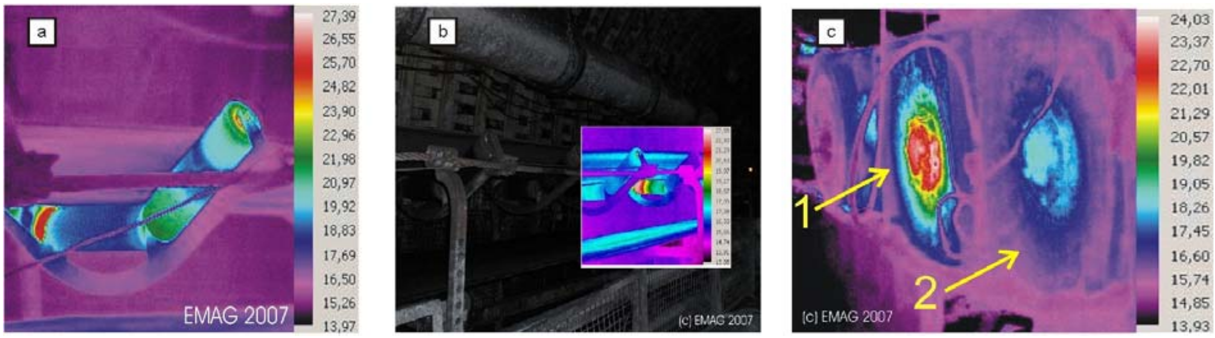


Figure 3.3.3-1: Thermal symptoms observed during pre-failure states of belt conveyor

Measurements were also taken at the belt drives. They proved the thermal phenomena were distinguishable even in case of lightly unbalanced load distribution (see **Figure 3.3.3-1 c**). The measured temperature differences were found large enough to be monitored by means of simple electronic sensors attached to gearboxes, engines and pulleys.

For the purpose of thermal monitoring of rolls different schemes and concepts have been studied by all partners involved. The key factors which have been analysed include:

- cost of overall system (number of nodes and price per node),
- measurement and communication schemes (fail-safety, response time, energy efficiency),
- maintenance issues (battery life/replacement, reliability, etc.)

The analysis led to the conclusion that overall cost of idler monitoring with use of WSN (taking into account current equipment, installation and maintenance cost) would be significantly high and therefore not much economically justified. For that reason further activities were focused on thermal monitoring of driving system for belt conveyors.

State of the art belt drive monitoring systems (in Poland) are commonly equipped with emergency bimetallic switches triggered only during serious failure (see **Figure 3.3.3-2**). Significant improvements can be introduced by on-line monitoring of gearboxes and drives with temperature and belt slippage sensors. Such an approach offers possibility to detect failures in advance and prevent serious incidents.

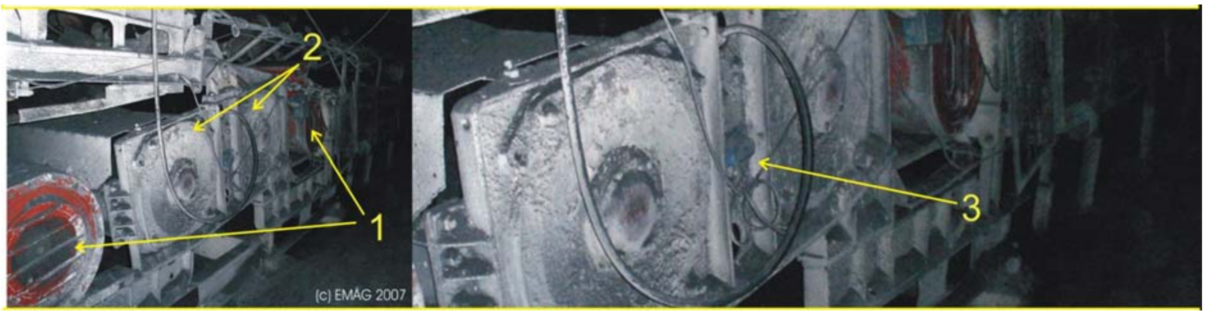


Figure 3.3.3-2: 1-engines, 2-gearboxes, 3-temperature safety switches

For that purpose an advanced application employing low power wireless sensors was developed.

The complete application (see **Figure 3.3.3-3**) consists of three sets of sensors (for redundancy reasons) consisting of identical transceiver boards – comprising RF transceiver, microcontroller and embedded temperature sensor. The temperature of the drum is monitored by two wireless sensors (S1,S2) installed and thermally coupled with it. By adding the Hall-effect sensor and set of permanent magnets the sensors will be able to monitor angular velocity. The sensors S3,4 monitor velocity of the belt (Vb) and Sensors S5,6 are for monitoring temperature of the drive M. By measuring temperature difference between ambient (Ta) and drum (Td) and comparing linear speeds of the belt (Vb) and drum surface (Vd) slippage phenomenon can be easily detected. Exceeding the threshold values for slippage and temperatures results in switching off the drive – this action is performed by the sink node which also enables online monitoring of all the parameters.

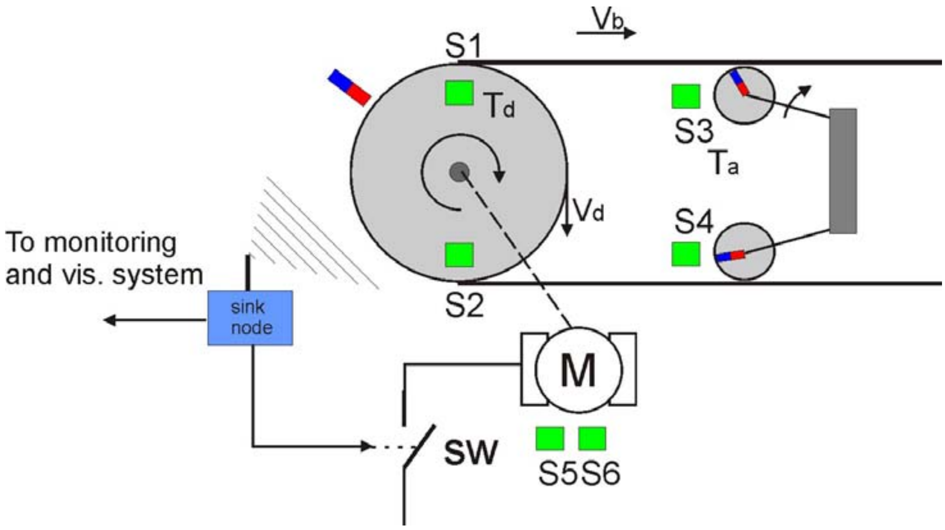


Figure 3.3.3-3: System for monitoring of the belt drive

First revision of software was developed for two chip ZigBee solution then it was ported to (SoC) based ZigBee platform (CC2430) as it seemed to offer many advantages. In further stage, before the final hardware was developed tests and measurements were carried out to evaluate performance of the developed software for preliminary SoC based sensor with use of CC2430EM evaluation module (see **Figure 3.3.3-4**).

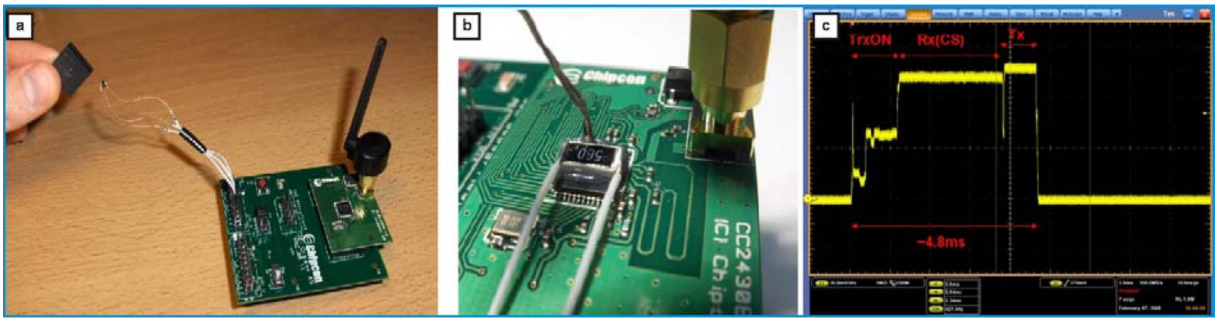


Figure 3.3.3-4: Performance tests of software for SoC based sensor

It was found that the Hall-effect sensor which was used didn't work correctly for higher switching frequencies. Additionally the calibration procedures for embedded temperature sensor were found cumbersome. Finally, the precise comparative measurements of power consumption led to the conclusion that ZigBee SoC based solution is too little energy efficient for the desired battery life. These gave rise to following improvements introduced to the final revision. The optimal hardware consist of separate microcontroller and wireless transceiver from Texas Instruments (MSP430+CC2500). For temperature measurement external factory calibrated temperature sensor of 0.5^{o}C accuracy was used. The Hall-effect sensor used for final design has high switching frequency which gives less than 0,2% measurement error for span of measured rotation speeds. For the wireless chipset a 'lightweight', however, robust open source networking stack software was used – 'SimpliciTI' available from Texas Instruments. The stack is optimised for use in star topology which is sufficient for the application. Porting the previously engineered software to that optimised platform wasn't much difficult and final laboratory tests proved its correct operation. Final revision of the sensor (see **Figure 3.3.3-5**) is low profile and compact (it measures only 39mm x 58mm x 13mm) and is powered from single CR2032 lithium coin cell. Its expected battery life for this particular application is more than 3 years.

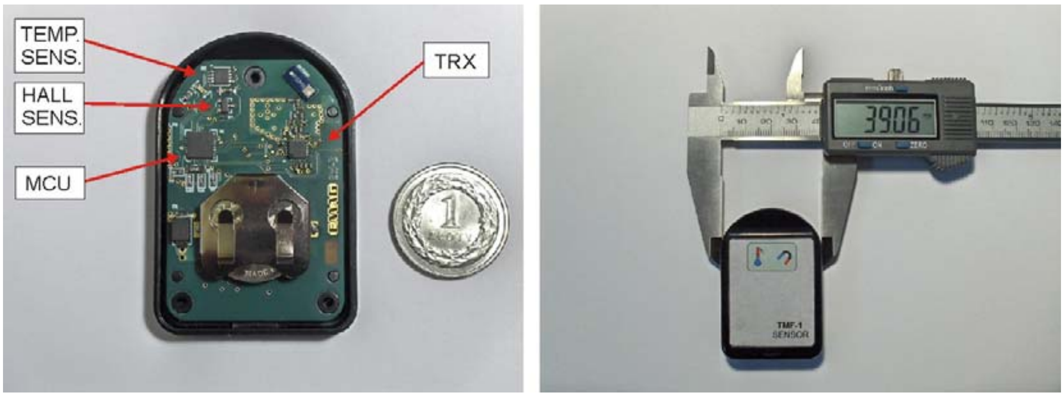


Figure 3.3.3-5: Final revision of low power wireless sensor

3.3.3.2 Self-organising networks for advanced monitoring of the infrastructure in mines (Activities Task 3.2)

The use of ISM band IEEE 802.15.4/Zigbee technology was proposed for the wireless sub-system and various topologies were studied. Radio sub-system suppliers were appraised, and the implementation of long hop length TCP/IP daisy chain and mesh topologies was considered. It was found that limiting the number of hops to 6 was a sensible amount in most situations. EmberZNet can maintain a consistent data throughput up to around 6 hops. This drop of is more severe in standard TCP/IP implementations.

Wireless mesh smart sensors - application development

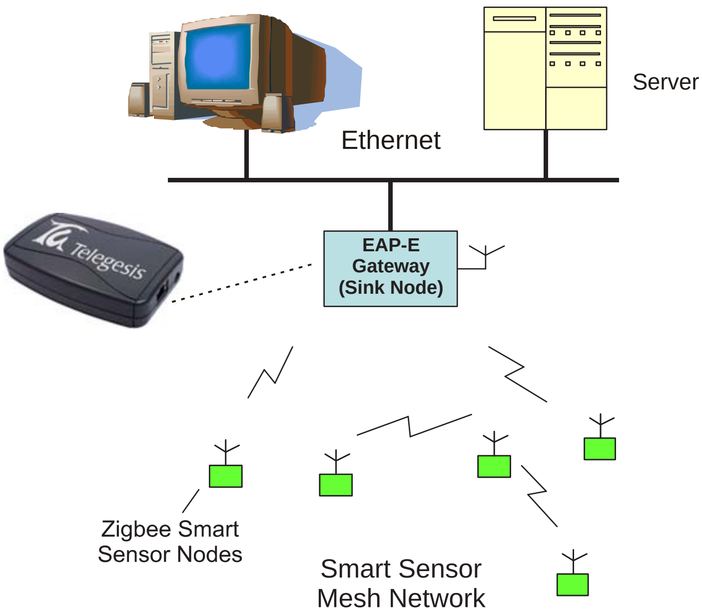


Figure 3.3.3-6: ZigBee Smart Sensor Network using Telegesis EAP-E Router Gateway Devices

An overview of the smart sensor application developed by MRSL is shown in **Figure 3.3.3-6**. The network has two separate types of WSN node; a 'sink' node and a 'sensor' node. The sink node acts as a data collection point for the sensors and gateway to an external PC or network interface. Upon receipt of a sink 'advertisement', sensor nodes will assign themselves to the 'sink' and start sending data. This application is suitable for a range of sensory data acquisition applications including: temperature monitoring, environmental monitoring, remote machinery telemetry and diagnostics.

Embedded Smart Sensor Application Features:

- The network was developed using EmberZNet technology – fully ZigBee PRO ratified – and ETRX2 radio modules incorporating the Ember EM250 microchips.
- Telegesis EAP-E (ZigBee to Ethernet) router provides the remote 'sink' node access. This is scalable to have several sink nodes with sub-networks of smart sensor devices

- The sensors are easily scalable. The sink node constantly advertises to look for new sensor devices within range.
- The ‘sink advertisement’ allows the network to constantly check and maintain links. Sensor devices will look for a new sink if the link is lost.
- The sink node acts as a gateway to interface directly to a PC via serial communication, or to a network using TCP/IP.
- The EM250 nodes contain on board 12-bit ADC inputs, therefore simplifying the hardware requirements for sensor applications only requiring this 12 bit resolution or less.

Associated high-level data acquisition software was develeoped using Microsoft Windows based Visual C++. An overview of the system is shown below in **Figure 3.3.3-7**. The aim of the application was to log and interface the sensory data through a larger network infrastructure. The server PC collects and stores the sensor data from a ‘sink node’ to an SQL database.

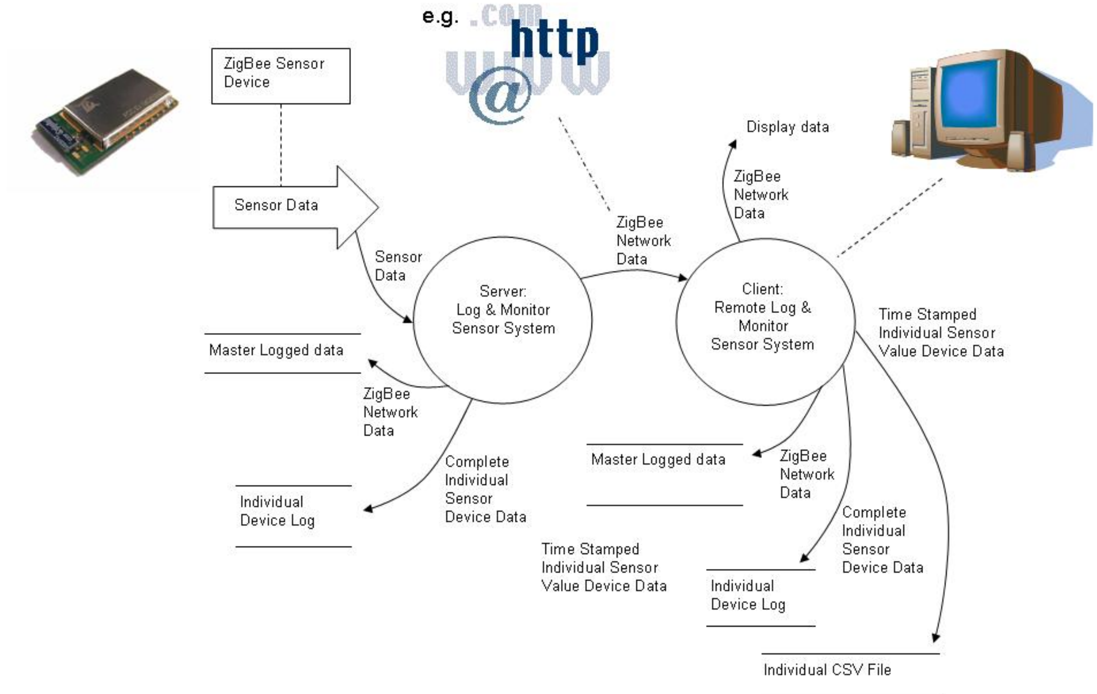


Figure 3.3.3-7: Smart Sensor Data Acquisition – Windows -based Application Development

The application was further developed using PHP to run on an Apache web server in order to permit users to remotely log on to the web server using HTTP. The software was written a way such that it was scalable for different types and numbers of remote sensor WSN devices. Whilst the primary intended application for this is a distributed temperature monitoring system for belt conveyor drives, it is suitable for a number of other types of sensor applications.

Fibre-optic based Ethernet has been installed in many coal mines in Europe, and internationally including the US and Australia. This provides the host network to support applications using the WSN described above. The software developed has provided an infrastructure to establish such applications for temperature monitoring or gathering other sensory data for environmental and mine infrastructure monitoring. The testing of the wireless mesh smart sensor network developed is discussed in ***Task5.2***.

To give necessary functionality to ZigBee sensor networks based on hardware developed in WP2 a generic management and data acquisition application was developed by EMAG. That software can be used for applications covered by areas of ***Task 3.2*** and ***Task 3.3*** and many other.

The software runs on the embedded web server based on the **NutOS** real time operating system and **Ethernut** open source hardware platform. The application interconnects ZigBee gateway(s) to the IP Ethernet network. It is possible to use TCP/UDP sockets or popular FTP, HTTP protocols. The developed data acquisition functionality is specifically designed to work in configuration with several ZigBee gateways connected to the data concentration system via intrinsically safe serial interfaces.

As such it offers seamless integration with ZIST transmission system used in Polish mines (see **Figure 3.3.3-8**).

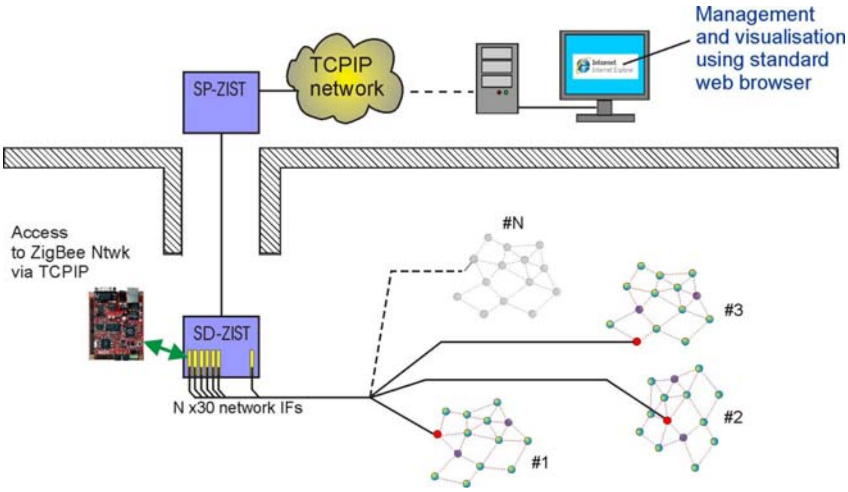


Figure 3.3.3-8: The structure of the data acquisition system using ZIST transmission system

The embedded web server provides HTTP / CGI based user interface to enable easy deployment and management of the sensor networks as well as give access to sensor data via LAN/internet connection. The user interface allows to:

- *assist in deployment (i.e. binding, adding new sensors to database, defining authorized MAC address pool),*
- *assist in management (remove sensor from system, set polling intervals for individual sensors, view status information),*
- *view data from defined group of sensors, authenticate users (with different privilege levels)*

The application performs cyclic update of data acquired from sensor network via serial link to ZigBee sink node. Each sensor is polled with a rate defined by its polling interval. Data is stored in repository file in non-volatile memory (RAM with battery back-up) managed in circular buffer style. External applications have access to the repository file via File Transfer Protocol (FTP) which can be used to synchronise with large SQL data base if necessary.

Based on the results of task 2.1 and in preparation of the underground tests within WP5, WSN-tests were performed using a leaky line antenna. This technology is described within task 5.2.

3.3.3.3 Monitoring Rock Stress (Activities Task 3.3)

The predominant part of the already existing measurement technology for rock mechanical movements is carried out up to now with well-proved offline methods. So that such important measuring data can be available as fast as possible, however, the previous concepts must be tailored to the new WLAN and optical fibre based infrastructure of the mines. With that possible online measurements with faster data-availability can improve the internal company course considerably. Due to the early recording of an increase of pressure in a roadway, the pressure reducing steps for the prevention of rock stress can begun very much sooner.

Since the physical relevant measured values for rock mechanics like pressure, extension and temperature change only very slowly, the demands on a corresponding measuring system are only small. And since only few measuring cycles with small bandwidths per unit of time are necessary for the measurement and transfer of the measuring data (where the power consumption is turn out extremely short), also battery operation can be considered for such measuring systems.

For this purpose the Wireless-sensor-networks (WSN) already available for industrial market seemed to be suitable in excellent way. In this case RAG as well as DMT favoured such a WSN which based on the transceiver-chip "Nano-Net TRX" from the company NANOTRON with the most extremely secure communication protocol CSS (Chirp Spread Spectrum). First tests with some Nanotron-based components run very promising.

At this place particularly the small current consumption of one Chirp-sensor should be emphasized, which can reach a service life of up to 5 years only with one small 3,6V Lithium battery. This was of great importance for the later intrinsically safe certification.

With the represented components it was only a small step to the planned net topology of the rock mechanical measuring system shown in **Figure 3.3.3-9**.

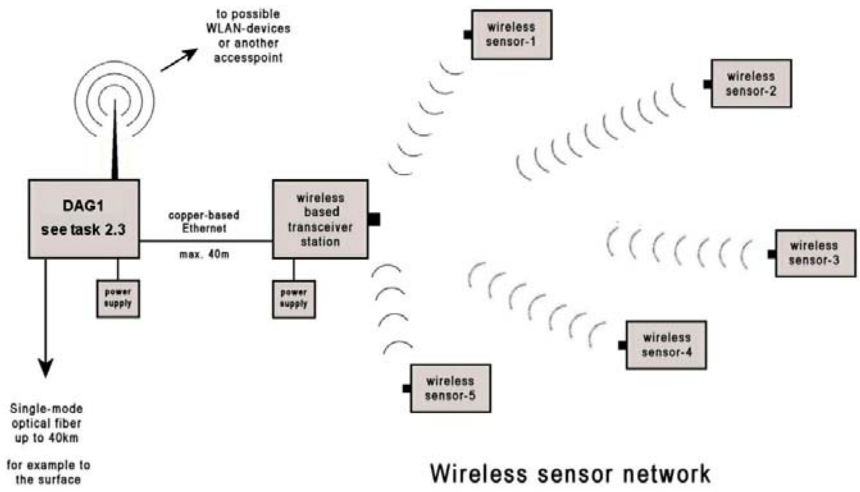


Figure 3.3.3-9: Topology of the planned rock stress measuring system

The sketch shows the concept of the rock mechanical measuring equipment including the link possibilities to the ETHERNET. From the right to the left the necessary development blocks for the commitment in the mining industry can be recognized: Firstly the measurement with the wireless sensors 1 to 5, secondly the data processing represented as transceiver station and thirdly the data transmission equipment realized with the Data Acquisition Gateway (DAG1) developed within ***Task 2.3.***

The description of the project work should be occur in reverse direction from left to right, where in first position the DAG1 from WP2 serves as an "entrance" to the plant network. This link-up is possible and freely eligible as both, single mode optical fibre interface with 40km transmission range or WLAN-connection to the next Accesspoint. The combination of the two units is realized here via an intrinsically safe copper Ethernet interface with a maximum transmission range of 40m and whose ATEX certification was carried out within the framework of a preceding RFCS project (EPCWCMS No.: RFC-CR-03003) .

The represented "transceiver station" fulfils here three essential functions at a time. The first provides the recording of the radio based measuring data of the Chirp-sensors 1 to 5, the second provides their processing and the third function their subsequent transfer to the Gateway. This all is managed by the commitment of the two devices. While the I/O unit is communicating with the Chirp-sensors via the Chirp Spead Spectrum telegram, the processor unit is instructed with the administration and the assignment of the measuring data. For the representation of the measuring data, the processor unit has an http-web-server that is reachable via an own IP address.

The power supply of the original units bought on the industrial market was exclusively fitted with 24V-inputs. As a result it was one of the main tasks to convert just these power supply units onto those ones with 12V usual in mining industry. In addition the electronic boards of the industrial devices should be provided with a potting compound (for the Ex-certification), since necessary circuit- and temperature-conditional changes should have hardly exceeded the justified expenditure.

After all completed calculations, developments and modifications a "base station" that unites a processor unit and two of the I/O-units within one housing. In **Figure 3.3.3-10** the rough draft, the opened- and the closed preproduction model are introduced. Since each I/O can manage up to 16 sensors, a maximum number of 32 sensors becomes possible with the two built-in I/Os. In the illustration this can be recognized by the two antennae for the two radio circuits each.

Figure 3.3.3-10*: *Prototype of the base station as sketch and as real one opened and closed.

For the real commitment in underground the case must be filled completely with potting compound, where the power supply terminals are positioned in an extra room without compound. A few necessary display diodes for the operation as well as for the parameterization of the sensors are visible through a pane of glass within the casing cover.

The main attention of the developments however, was focussed on the necessary components for the rock mechanical radio-sensor. This consists of both, the circuit-board of the Chirp sensor and of an own electronics development for linking-up the physical measuring sensors. Since in the case of rock stress measurements almost rock pressures or extensions are registered, the development could be enclosed onto those of a strange gauge amplifier and onto those of a linear extension amplifier.

The original circuit-board of the Chirp sensor was supplied with a lithium cell of 3,6V, which service life of 3 or more years was guaranteed by the manufacturer. This energy-balance was a challenge for us, to achieve similar values also within our own developments. For that especially for battery supply optimized semiconductor chips were chosen for this purpose on the one hand and optimization calculations for the possible and necessary measuring cycles were carried out on the other. On the left of **Figure 3.3.3-11** the complete sensor electronics is represented, which is divided up into three blocks. The bought radio based Chirp-sensor forms the utmost right block while the self developed electronics for the strange gauge link-up can be seen within the left block. The battery supply in the middle block is valid for both units. An extremely power saving microprocessor forms the heart of the circuit in the left block, which intern timer (with sleep-mode procedure) controls the time slots for the recording-cycles, for the processing as well as for the transmission of the measured data. Additionally the processor could also be used for special functions like battery- and cable-check of the strange gauge in this case.

After the test of the 3,6V Li-Ions accumulator fails during ATEX-certification, three primary cells with 1,5V each were used, whose energy transfer can be modulated by the processor.

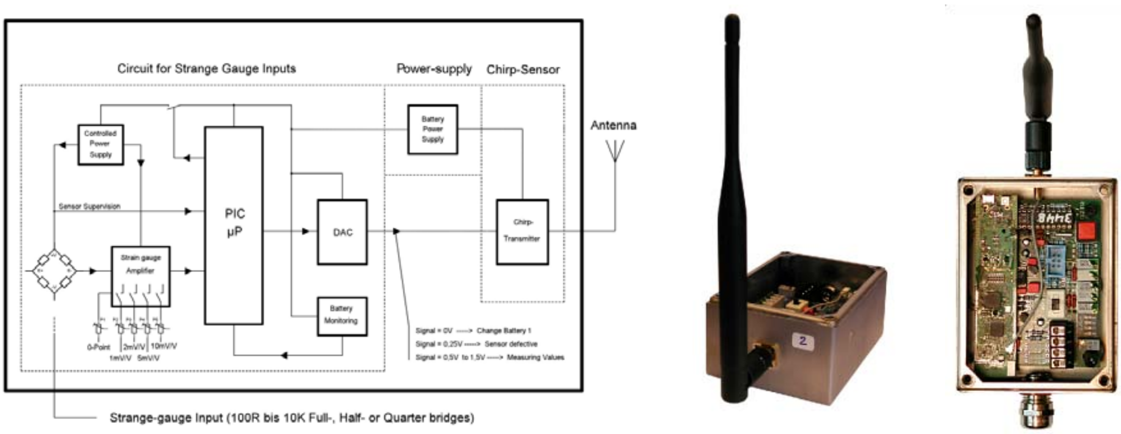


Figure 3.3.3-11: ***Block diagram and prototype models of the complete rock-mechanical-Sensor***

For the adaptation to a linear extension sensor this circuit could be taken over up to the supply of the bridge. With the commitment of the processor it is also possible in this case to carry out a linearization of not linear resistance pick-ups. On the right of **Figure 3.3.3-11** two photographs of the ready rock mechanical sensor preproduction models can be seen (here already with external antenna). The three primary cells for the power supply are positioned and fixed under the seen circuit-boards within the case. Next to the work for the certification, continued tests were carried out, where the suitability for underground application has to be validated repeatedly (*see **Task 5.2***).The certification itself was finished within project running time, approved with the commitments of Ex I M2 Ex ib I and registered under: BVS 08 ATEX E 248

Rock stress measurements are usually done by AITEMIN using total pressure cells, used to measure the total pressure in the soil mass or structure, in order to determine the magnitude and direction of stresses.

Figure 3.3.3-12: Total pressure cells

Total pressure cells are based on strain gauges. A strain gauge is basically a resistive element which changes in length, hence resistance, as the force applied to the base on which it is mounted causes stretching or compression. Because of this characteristic, typically the gauges are bonded to the surface of a material and measure its dimensional changes when put in compression or tension.
Commercial total pressure cells are available with 4-20 mA output, which can be directly connected to the wireless sensor nodes developed within this project. Nevertheless commercial cells have the problem of a relatively high power consumption to be excited from a wireless sensor node.
Measurement with miniature cells are proposed, using cells based on a Wheatstone bridge. Some cells have been identified, with a +5V excitation voltage (perfectly compatible with a battery powered node). In order to use this kind of cells, a conditioning circuit in needed to interface with the wireless sensor node. Using this technique, an extremely small resistance change must be measured. The bridge circuit is widely used to convert the gauge’s microstrain into a voltage change than can be fed to the input of an ADC (Analog to Digital Converter), due to the output of the bridge is proportional to the displacement: $\underline{V_{OUT} = V_{EXC} \cdot X}$ where: X = relative change in resistance, $\Delta R/R$ and V_{EXC} = excitation voltage applied to the bridge.
Note that output depends on the excitation voltage, so the cell must be excited with a well regulated, low-noise source.
AITEMIN’s activities have been focused on the design of the signal conditioning circuits to connect a miniature cell to the wireless sensor node. The output from the cell is a low level signal (2 mV / V), very susceptible to electrical noise. Therefore signal conditioning is necessary, as well as proper shielding. The design has been done according to the following circuit diagram (**Figure 3.3.3-13**):

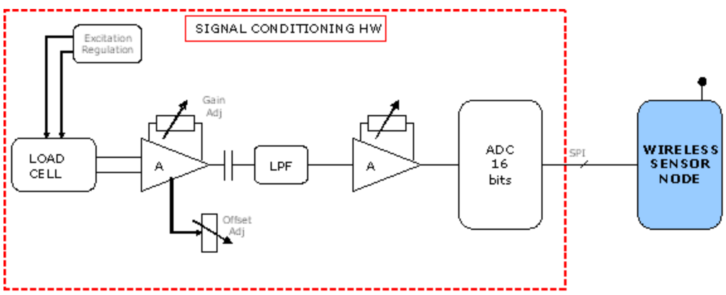


Figure 3.3.3-13: Signal conditioning circuit for Strain Gauge Interface

The output of the signal conditioning circuit is digitized using a 16 bits ADC with SPI output, which is directly connected to the wireless sensor node.

As their contribution to this task, RMT designed a remote stress/displacement monitoring system based on measuring strata movement or dilation and relaying the information to a portable reader (***Task 3.5*** and ***3.6***) with wireless access. This remote stress/displacement facility is a development of the RMT dual height mechanical tell tale which relies on visual interpretation of two scaled tubular ‘telltale’ indicators attached by wires to spring anchors fixed up a drilled hole in strata above the roadway. Any dilation or bed separation of the strata will appear to pull the indicators up into the hole. Regular observation of the tell tale indicators relative to the roadway roof line is used as a way of monitoring strata condition/dilation and hence the effectiveness and safety of the roof supporting arrangement. The wireless system is an adaptation of these mechanical telltales and the wired remote reading telltale system developed under previous ECSC and RFCS projects. On a ‘wake-up’ call the stress/displacement monitoring unit turns on the sensing element (coil and ferrite rod) circuits, measures and down loads the relative strata movement.

The low power wireless module exploited is based on the same Bluetooth device as was adopted for RMT’s wireless mines rescue communications system, see **Figure 3.3.3-14**. Bluetooth module (Class II) programmed to operate two data ‘UART’ channels and remain dormant as a ‘slave’ device. Each wireless stress/displacement remote unit’s information can be down loaded, wirelessly, to a portable interrogation instrument (***Task 3.5***).

Wireless rock stress measuring devices deployed in coal mines are subject to ATEX limitation. As with all remote wireless sensor devices the power source is a key component. In this application it was feasible to have a twin cell Ni MH battery to operate the device for life. Following initial tests of a prototype the stability of this basically analogue circuit was marginal, primarily because of the added safety resistance and lower capacitor values, a necessary part of the ATEX requirements. A redesign employed a novel way of stabilising the circuit with the adoption of the newer available low power and low-drop-out regulator. This had the effect of multiplying the effectiveness of a decoupling or smoothing capacitor (a 33µF capacitor reduced to less than 1µF).

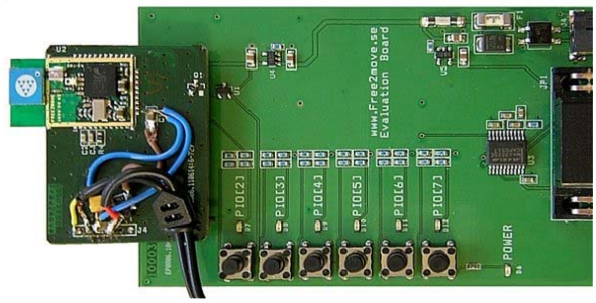


Figure 3.3.3-14: Bluetooth module with audio interface, note (blue) integrated antenna.

Tests between -20 and +40 degrees C demonstrated repeatable circuit stability behaviour. The average drain current at 3.0 Vdd was calculated to be approximately 18 µA, with daily reading 5 days a week, enabling two AAA batteries to last as long as their shelf life. Shelf life for Ni MH will be very dependent on temperature and at 30 degrees C it could be as low as 5 years but at 10 degrees C it would be nearer 10 years. The low powered wireless interface is based on the same Bluetooth device as that adapted for the m-Comm wireless link system.

3.3.3.4 Development of an underground RFID-based navigation and tracking system for machines, material flow and persons (Activities Task 3.4)

The Sago mine disaster in West Virginia in early 2006 highlighted the critical need for a location, tracking and navigation capability in emergency situations. In response, the US Mine Safety and Health Administration have requested information on technologies and research which could satisfy these requirements.

Following on from the research in **Task 2.4**, further work was undertaken to reappraise the respective merits of RFID versus emerging wireless networking technologies for the purposes of providing zonal location information underground. A review of industry practice identified that a number of active transmitter or transponder-based solutions have been introduced into mining for access control, vehicle and personnel deployment monitoring and zonal location and that generally all of these approaches use proprietary technology. In each case, hardware for local interrogation systems can be relatively cumbersome and costly to install, particularly where low frequency inductive transponder technology is used because these systems require substantial coils to generate interrogation fields of appropriate magnitude and physical geometry. For this reason, underground electronic location determination systems employing transponder-based technologies have been relatively expensive if a substantial number of underground reading points have been required. The consequence is that reading stations have only been installed at critical points, and the ability to localise staff or materials in real-time is limited to a crude zonal basis. Therefore it was judged that active-type transponders using wireless sensor network (WSN) technology is the most versatile and cost effective solution to active underground tracking of personnel and vehicles in underground mines. The MRSL concept of the underground tracking system using WSN was discussed in **Task 2.4** and the development of the system is discussed later in **Task 4.6.**

One significant drawback of both RFID and active transponder type tracking is that the systems can only achieve a relatively 'coarse' approach to location awareness. A review of more accurate wireless locating techniques is summarised below.

Wireless Location Techniques

The most complex of the location determination problems is to locate an arbitrarily orientated wireless network device in a two and certainly a three dimensional space to a high degree of accuracy. In this case, relatively complex signal processing is required, possibly in conjunction with a requirement for reference devices. The use of Zigbee with RSSI to determine positioning has been considered. However, the solution of the unconstrained location problem may be insoluble. In any event, the associated computational processes are non-trivial. Location estimation schemes used in long-range communications, such as wireless cellular networks, include time of arrival (TOA), time difference of arrival (TDOA), and received signal strength (RSS). Exploiting RSS in short-range communications could provide a low-cost improvement to the accuracy of location determination.

The primary technological approach developed within this project involves RFID / tracking applications using low power wireless mesh networking technology e.g. Zigbee / IEEE 802.15.4 technology. There are essentially two different groups of location techniques using wireless technology; 'Zonal Location Tracking', as in traditional RFID schemes where a mobile node is only recorded passing a reader station or point, and 'Positional Location Tracking' where the exact position of a mobile node is either monitored or the node only requires to know its location (e.g. GPS). The 'Zonal Location Tracking' approach was developed under this project. In underground environments, 'positional' rather than 'zonal' tracking would entail a significantly more complex implementation, requiring significant further research. Zonal tracking systems were given initial consideration during this project. These techniques are discussed below:

Indoor Specific Techniques:

Cricket Indoor Location System: Researchers at MIT (Priyantha *et al*. 2000) describe an indoor location tracking system specifically aimed at wireless applications. The "crickets" rely on a combination of RF and ultrasonic transmission. The TDOAs of the ultrasonic and RF beacon signals are used to determine the distance between a cricket 'beacon' and 'listener'. The combination of ultrasonic and RF travelling at different velocities helps mitigate the problem of multipath in an indoor environment. However, how effective this type of system would be in a multipath rich underground environment was not investigated.

With the assistance of DMT, the RAG has tested a special software that was able to determining the position of WLAN devices in mines. Both, WLAN access points as well as pocket PCs were utilised for these tests. The tests formed the basis for the visualisation of RFID based navigation, tracking and localisation. The procedure for localising mobile WLAN devices utilises the field strength analysis which is continually performed by the pocket PCs to determine available access points. Thereby the field strength decreasing with increasing distance from an access point can be utilised as measure for distance. A software tool is running on the pocket PC which cyclically transmits the measured field strength to the accessible access point. The access points forward the values to a central computer. This computer then determines the position of the pocket PC. The qualitative reliability of this procedure will be better, when more access points are available. By appropriate differentiation methods between the individual field strength values, a value can be determined that represents the position of the WLAN device in the mine in relation to the known position data of the access points. The tests have shown that it is possible to localise mobile WLAN devices with a deviation of only a few metres. (The access point range depends very strongly on the geometry of the mine, and it is also affected by incorporated iron and steel structures.) The position can finally be indicated in the 3D model of the mine. A test was performed underground in the Ost mine (Bergwerk Ost); to this end a roadway was selected with a larger number of integrated access points (AP). An employee with an activated pocket PC moved along the roadway and the position of the pocket PC detected was visualised in the three-dimensional picture of the drifts (in the ProNet software, **Figure 3.3.3-15**). All the tests yielded results, which were positive throughout.

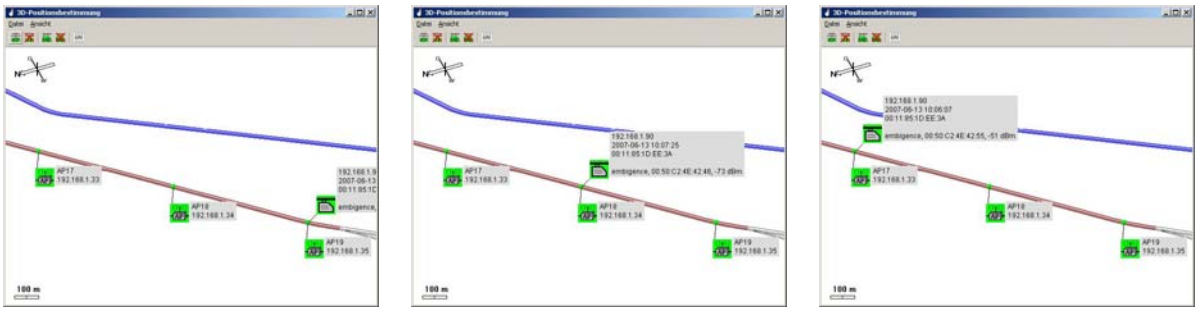


Figure 3.3.3-15: Path of the PC in the Ost mine, underground from AP17 via AP18 to AP19

A further second test was performed in the RAG training mine (TBW). During this test an employee with an activated pocket PC moved through the drifts and the plough face in the training mine. For visualisation purposes a software was used which recorded and displayed the path.

For this test 4 access points of different manufacturers were installed in the training mine. The Cisco access point was installed in the multimedia room, one Embigence access point in the area of the raise / blind shaft (southern district of cross-drift), the second Embigence access point in position 5 and a Becker access point in the plough face (**Figure 3.3.3-16**).

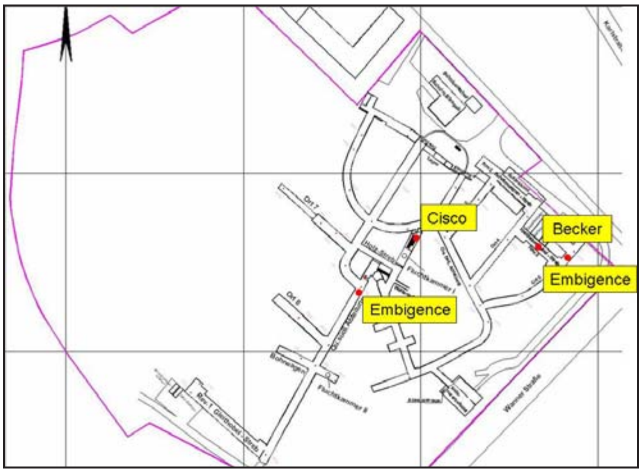


Figure 3.3.3-16: Position of access points in the RAG training mine

The left picture of **Figure 3.3.3-17** visualises the path from the Cisco access point into the direction of the raise, position 5 and back to the Cisco access point. The right picture of **Figure 3.3.3-17** depicts the path from the Cisco access point (multimedia room) to the raise, then into the direction of position 5, back to the Cisco access point, thereafter into the plough face and back to the raise again.

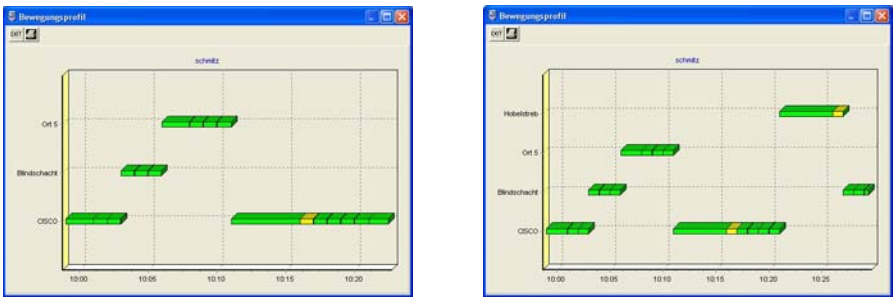


Figure 3.3.3-17: The movement profile in the training mine

For material tracking the complementary solution developed and described within task 2.4 was applied and underground tested within WP5. The visualisation technology developed for that, is based on the tests of the localisation of pocket PC's using the WLAN access points mentioned above.

3.3.3.5 Wireless Sensors Access with PDA's (Activities Task 3.5)

To make use of the data collected by the WSN, devices and applications to access the information in every place are needed. This would be done by means of wireless devices accessing to the network for

i) gathering data;
ii) updating sensor's O.S. remotely or
iii) managing and administrating the network.

The WSN must be able to communicate with an external control system. This function is done by a Wireless Control Unit, but nevertheless it is also important to access the information locally. The architecture of the system, considering both the wireless system and a wired system where the first one is integrated, would be the following (the blocks surrounded are been developed under the current project., **Figure 3.3.3-18**)

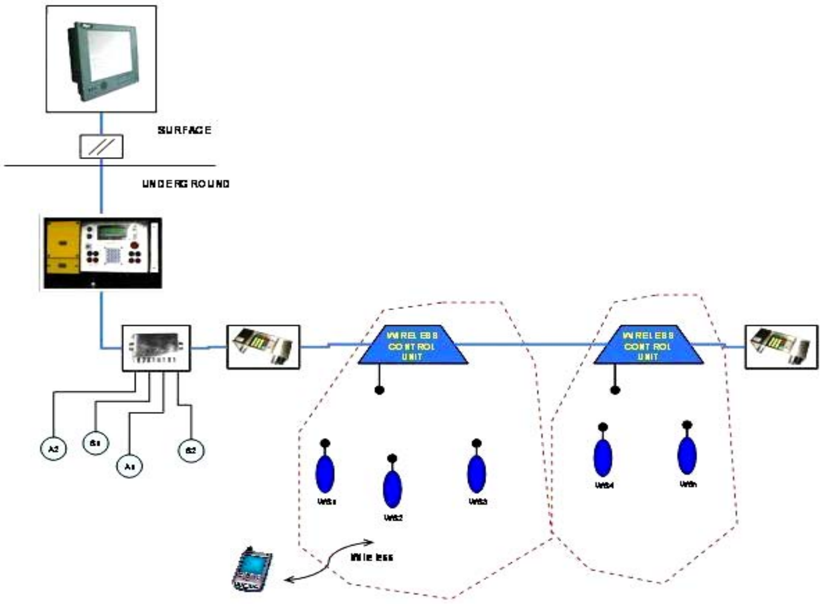


Figure 3.3.3-18: Monitoring System including WSN access units

Local access to the WSN is done by means of a Pocket PC with an appropriate wireless interface. A part of these activities have been focused on the access through devices with ZigBee capabilities, allowing a direct access to the network coordinator, without the need to interface with a wireless control unit.

For this application a useful feature of the embedded control firmware on ETRX2 modules could be used. ETRX2 firmware distinguishes a fourth type of node, apart from the standard FFD (coordinator and router) and RFD: *sink node*.

A *sink* node is intended as a central receiver of data. This feature allows a coordinator to leave the network after starting and establishing it. A separate node can be selected to operate as a data sink (only one sink node could be defined per network).

This way a pocket PC could be used as coordinator for starting all the networks, and after defining the sink node, leave the network to be used for the starting of another network (outside of the coverage area of the first one).

For the development of the applications an adapter node can be connected to a Pocket PC. For this purpose, the manufacturer of the Zigbee modules offers some products to adapt a pocket PC or a computer, as can be seen in the picture below (**Figure 3.3.3-19**)

Figure 3.3.3-19: Zigbee adaptors for Pocket PC and for Laptop

In order to prove the concept, a software application has been developed to access to networks data from a portable device, i.e. a PDA. Basically, the application implements a network coordinator into the PDA, allowing to the user get the sensor data 'in situ' showing the information in real time on the device screen. It can be very useful during the sensor installation or maintenance tasks, due to it allows performing any change in the adjustement, calibration or configuration of the sensor elements with an immediate graphical feedback.

The use of a PDA also makes possible an easy interactuation way between the user and the network, for example, to change the status of a machine controlled by a device based on ZigBee is possible by means a GUI (Graphical User Interface) on the PDA screen. Therefore, all the elements of an installation (fans, elevators, railway trucks, etc.) could be managed through only a single apparatus where the GUI is automatically adapted to control the machines or elemens located next to the user. To perform the application, the PDA accesses to the network by mean of a Compact Flash ZigBee adapter. This adapter is based on Telegesis ZigBee modules, already used in the development both the network coordinator (***Task 2.3***) and the universal wireless node (***Task 2.1***). This fact allows using part of the program code previously implemented into these devices, saving time and making easier the system integration.

Another advantage of using the same devices family is the remote access to the internal module parameters. It permits to access (and also change) up to the lower level parameters of the remote modules, getting a total control over the network and making possible to perform diagnostics procedures over an specific node (or even on the whole network) with high detailed feedback information. This information could be very useful to detect possible weaks points (especially in a complex networks) or performing a system optimisation. In addition, a embedded firmware update of the remote nodes can be also performed. To prove the concept, a simple application was carried out. The application consists of a PDA (a commercial device was used for testing purposes), acting as network coordinator, and a universal wireless node with a differential pressure sensor mounted on it (**Figure 3.3.3-20**). The coordinator reads the sensor value once per 10 seconds, saving it in memory for a possible later postprocessing and showing the taken measures on the screen in real time.

Figure 3.3.3-20: Universal Sensor Node with differential pressure sensor (left) and a PDA including ZigBee adapter (right)

The following table shows a fragment of the data collected during the test (**Table 3.3.3-1**). The first column presents the timebase. The second column shows the pressure value given out by the sensor element. The third one informs about the remote node battery voltage and the fourth indicate whether the sensor value has been uptated since the last coordinator data request. Other events as link lost are also displayed.

Tiempo (seg x 10)	Presión (Pa)	Batería (V)	Actualizado
162	0.01	8.1	SI
163	0.01	8.1	SI
164	0.01	8.1	NO
165	NO CONECTADO	---	-
166	0.01	8.0	SI
167	0.01	8.0	SI
168	0.01	8.1	SI
169	0.01	8.1	SI
170	0.01	8.0	SI
171	0.05	8.0	SI
172	0.63	8.0	SI
173	1.25	8.0	SI
174	1.25	8.0	NO
175	2.45	8.0	SI
176	2.51	8.0	SI
177	0.23	8.0	SI
178	0.05	8.0	SI
179	0.01	8.0	SI

Link between node and coordinator lost

The sensor data has not been updated in the last 10 seconds

Sensor response to external stimulus

Table 3.3.3-1: Remote sensor values logged by a PDA through a ZigBee network.

DMT as well as RAG have decided to be busy in engineering a possibility to use the already certified available PDA “i.Roc 416-Ex” in combination with their common used “Wireless Sensor Networks” based on Nanotron’s Chirp technology. A lot of possible new considerations and tasks could be generated in this case. Direct measuring of the sensor values on site, polling of the battery status as well as performance and quality tests of the transmission functions are only a few examples for suitable applications. For this purpose and with consideration of the used communication protocols of the sensor, a tailored software was developed for the application on the certified PDA.

The favored PDA i.Roc 615-Ex is a robust industry handheld-PC, that based on WindowsMobile® and next to an infrared (IrDA)-interface it possesses also of a Bluetooth and WLAN-802.11b-functionality. With its small dimensions of 210 x 100 x 50mm and his moderate weight of 1,3 kg it is suitable for the mobile commitment in underground.

Furthermore the PDA owns a SD-slot that allows to design respective software developments concerning the storage requirement more freely and to guarantee also future enlargements. With the 400 MHz XScale processor and the display with a solution of 320x240 pixels it is furthermore possible to represent varied and extensive information with small latency times. **Figure 3.3.3-21** shows the device in the already Ex-certified variant.

Figure 3.3.3-21: Intrinsically underground-PDA“i.roc“

The initial idea to create a possibility, where the PDA could have communicated with the Chirp-Sensors in direct way or via a media converter (for example from Bluetooth to the sensor-own Chirp protocol) (see corresponding design right above in ***Figure 3.3.3-22***), had to be rejected to the middle of the project runnning time unfortunately again. Here a time-near relief with necessary Soft- and hardware couldn’t be guaranteed to us by the manufacturer. With the necessary hardware modifications also a change of the serial model would have had to occur furthermore, which would have justified the price of one sensor only by manufacturing a large number then.

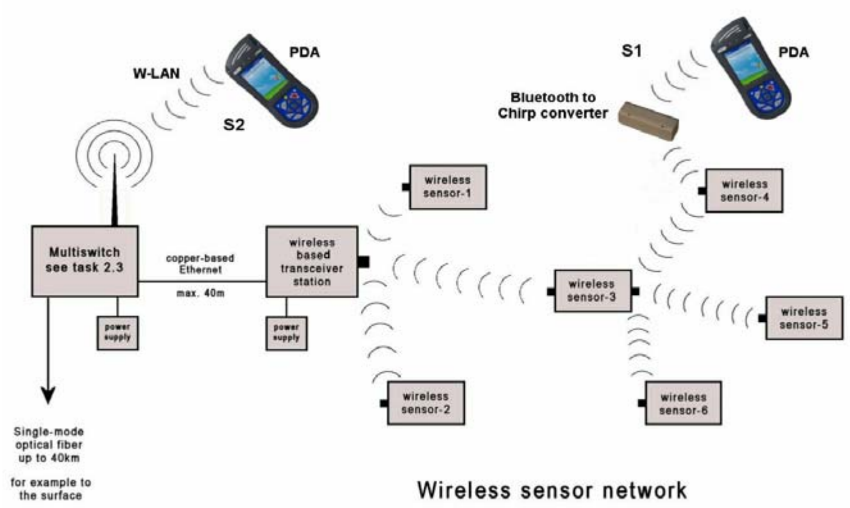


Figure 3.3.3-22: Wireless-Sensor-Netzwork with possible PDA-connections

In order to get a rapid and satisfactory solution for this problem at last, we decided to take the way via the WLAN-communication (to be seen on the upper left in ***Figure 3.3.3-24***). For this purpose a client-software was developed for the PDA, where the communication within the net could be guaranteed with the additional development of a corresponding server-software. With this tools it is now possible to record the the necessary data of the individual radio-sensors via the mobile PDA.

For the detailed representation as well as the test of the software under real conditions see ***Task 5.2*** and also the deliverable D5.2 (report: 'Underground trials of Sensor Networks').

Initial testing was conducted with CSR chip Bluetooth units and ITRONIC Duo-touch tablet PC with a Bluetooth wireless interface card. The ITRONIC ruggedised PC operates as normal a windows operating system and is effective at testing data acquisition software. Once the Bluetooth units were fully configured as required by RMT, i.e., identity arrangement and time-on data formats, etc., then the concept was deemed acceptable.

As reported under ***Task 3.3***, the selected RMT remote sensor technology for rock stress/displacement monitoring is based on a commercial Bluetooth wireless module (see ***Task 1.3*** and ***4.4***). With a standard Bluetooth wireless module it was possible to select and exploit commercial products for accessing data. For RMT, the ECOM Instruments GmbH mobile computing intrinsically safe PDA i.roc 612-Ex was the logical choice with its optional integrated Bluetooth 1.1 (Class II) interface/card.

The ECOM Instruments mobile computing intrinsically safe PDA i.roc 61 proved capable with the RMT preproduction remote wireless units. In simulated mine trials the practical limit on operating range is, in some circumstances, less than 15 m line-of-sight. This was considered to be acceptable

3.3.3.6 Gathering and Collation of Operational Data for All Wireless Devices (Activities Task 3.6)

The candidate wireless technology for the mines rescue wireless communications and rock stress remote sensors is the CSR range of Bluetooth Class 2 chips. They are supplied with FCC, CE and IC compliance certification, i.e., they are EMC approved and are low power radio licence certificated world wide. Therefore the tests carried out by RMT under this task of the RAINOW project were directed at the application and as a means of assessing the system's interference performance under operational conditions.

Electromagnetic (EM) Interference

The electromagnetic (EM) interference tolerance tests of the Bluetooth chip audio configured (Free2move) wireless modules demonstrated were better than expected. When the Bluetooth embedded software (stack) is correctly set-up, i.e., to enforce individual device/chip authorisation and synchronisation, then it is impossible to cross-link any wireless system operating on or around 2.4 GHz. The possibility of having another device with the same identification is remote.

The most likely outcome of co-channel interference, if the anti-collision algorithm is overloaded, is loss of audio data causing 'glitches' and, in the extreme, the loss of synchronisation, sometimes termed 'drop-out'. In fact, it proved very difficult to create blocking interference between two Bluetooth devices. High powered 2.4GHz devices, nearing the legal limit for low power wireless licence exempt devices, could swamp or overpower the receiver front end circuit when placed within less than 10 cm of each other. This was considered to be highly unlikely in the real life situation and if such a high power device was present in a rescue situation then by only moving a few metres away communications would be quickly restored. The WiFi and Zigbee devices tested for interference with the Bluetooth (Class 2) unit did not cause loss of transmission over a 10m set distance in an open laboratory environment. When a Bluetooth SCO connection is established the performance or throughput will equate to streaming raw UART data. This SCO mode does not have the error repeat function; it provides time-bounded communication for time sensitive services such as voice. Either way it would appear that the voice channel option is more interference tolerant.

The same interference tests were conducted with an ultra-wide band (UWB) system. The PulsON 200 evaluation kit from Time Domain Inc., could be configured to demonstrate:

a) distance against data throughput,

b) distance between two devices and,

c) angle of arrival of signal, i.e., direction.

RMT was primarily interested in UWB technology as the best solution to overcome multi-path propagation in tunnels and confined spaces. In theory the UWB system should be less affected by interference between itself and other wireless systems. This was confirmed within the limited tests undertaken. There was no apparent interference between the pulse radio system and the conventional 2.4GHz wireless systems. The PulsOn radio system used was very low broad band distributed power intended for a range of about 20 m. The susceptibility of the PulsON radio's input stage to being overloaded, or swamped, by Bluetooth transmission was higher than expected. The manufacturer commented, when questioned, that the kit was designed and made in around 2001, using discrete components.

Effects of Metal Structure

Interference from metal-work coupling into the antenna system was investigated at the same time. In short, the proximity of metallic objects to the device (antenna) can reduce the range of the wireless link but not as much as expected. The effect is sometimes difficult to detect because of the correcting effect of the Bluetooth transmit power protocol; a received weak signal will trigger the transmitter to increase output power. This give an abrupt loss of signal as it nears the limit of its range. As predicted from the near field theory the device's antenna has to be within a few cm of a metallic ground plane to have a pronounced effect. The effect on reception of metallic object shielding is no more than a 10dB drop, on a 10 m circle about the transmitter. Placing a random collection of metal objects did however cause drop-outs but these were very difficult to locate with a handheld device. This suggests that the locations of 'null-points' are very narrow and as a consequence may not be problematic in operational scenarios. Other issues of the Bluetooth wireless modules'effectiveness are addressed under ***Task 4.4***.

Audio Interference

As the m-Comm wireless system is primarily a voice link, the possibility of audio interference had also to be considered. A number of audio interface, pickup and microphone devices were examined, see ***Task 4.1, 4.3*** and ***4.4***. The throat microphone had been the obvious solution to gaining interference free voice communications but the possible high heat and humidity caused the wearer to suffer uncomfortable neck rash. As a result, the production units will include optional plug-in microphones and earphones as well as standard built-in audio pickup and speaker devices.

Wireless Interference Tests

This work was undertaken by MRSL to determine the degree to which ZigBee, Bluetooth and 802.11x WiFi will cause mutual interference in a mine environment and to make recommendations for their interoperation. It was decided that it is probable that at least three wireless data communication standards – ZigBee, Bluetooth and one of the 802.11x WiFi standards – would likely be required to fulfil the needs of the RAINOW project (and subsequent mine applications). It is expected that future underground mining operations will use a range of different wireless standards for different applications and these systems may operate in close proximity. At present, all these standards operate in the 2.4GHz ISM band with the potential for causing mutual interference. Initial research identified that Bluetooth and some 802.11x WiFi standards can cause mutual interference, with a corresponding reduction in data throughout and range, when operating in close proximity.

Results

An overview of the extensive tests and results carried out between four wireless standards is given below. Because the number of potential couplings of the various wireless technologies is large, a full evaluation would have resulted in an impractically large test matrix. Therefore only those technologies identified as being potentially useful in the mining environment were considered. Two reference standards were used (i.e. non-proprietary-enhanced); 802.11g and 802.11n. Furthermore, since only one WiFi standard is likely to be in use in any one mine (or at least in any one area of a mine), the effect of 802.11g interfering with 802.11n and vice versa were not considered. Regarding Bluetooth, tests were carried out on Bluetooth V2.0 (a recent standard) which includes an adaptive frequency hopping feature for reducing the impact of interference from other services.

The procedure involved measuring the throughput of the link being interfered with for various ranges, while also altering the range between the receiver of the link being interfered with and the transmitter causing the interference. The tests were carried out in a disused railway tunnel in Ashbourne, Derbyshire, UK. Previous tests in this location had shown that propagation here is representative of tunnels in general, exhibiting similar characteristics but with a somewhat lower attenuation rate due to the comparatively large cross-sectional area. The photographs below in **Figure 3.3.3-23** show testing in progress.

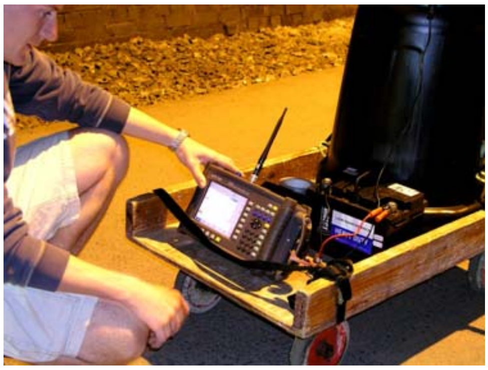



Figure 3.3.3-23:   Ashbourne Railway Tunnel Interference Tests

The tests gave a two-dimensional array of results that were represented in various ways for easy analysis. The graphs below in **Figure 3.3.3-24** – which relate to Bluetooth V2.0 interfering with 802.11g – are representative of the results obtained for each of the 10 test couplings. The contour and surface plots show the full data set, the left-hand line graph shows 802.11g data throughput vs. range at each separation between the Bluetooth V2.0 transmitter and the 802.11g receiver, and the right-hand line graph shows 802.11g data throughput vs. separation between the Bluetooth V2.0 transmitter and the 802.11g receiver at each 802.11g range.

In summary it was concluded that ZigBee, Bluetooth and 802.11x WiFi are capable of interoperation, so long as certain minimum separation distances are met, although the choice of 802.11x WiFi standard is critical.

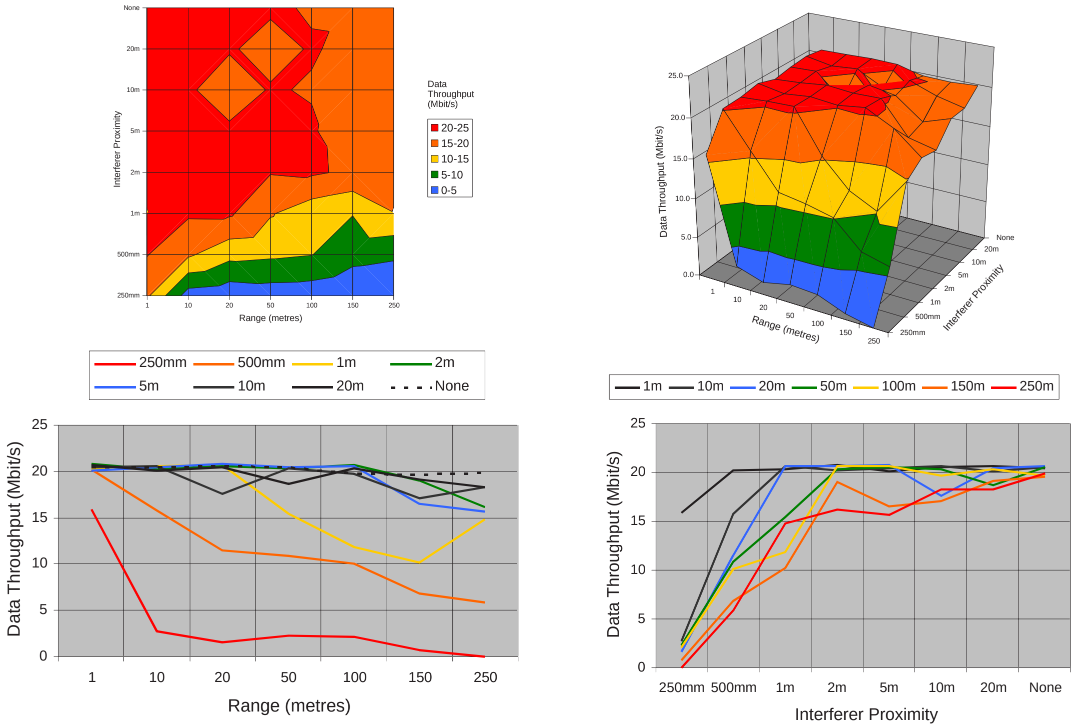


Figure 3.3.3-24: Bluetooth interfering with 802.11g Results

The recommended pairings are shown below (**Figure 3.3.3-28**). The grey box indicates a pairing that was not the subject of tests (because multiple WiFi standards are not envisaged in a single area of a mine), and the red box indicates the one pairing which is not capable of interoperation. Green boxes represent pairings that are capable of interoperation. Where a recommendation of the minimum separation can be made on the basis of the test results, the distance is shown within the corresponding green box. Despite the simplicity of this summary table, it should be borne in mind that these conclusions are based on 479 measurements of data throughput on ten test couplings of wireless communication standards.

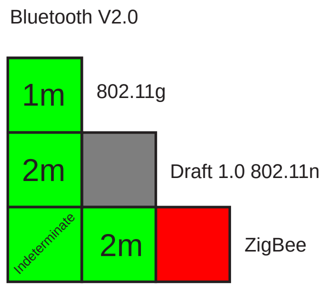


Figure 3.3.3-28: Wireless Interference Test Results Summary

3.3.4 Development of personal area networks for tracking, monitoring and guidance under health & safety aspects (Activities WP4)

3.3.4.1 Development of smart personnel sensors for health and safety values (Activities Task 4.1)

The initial work was to derive an operational and clinical (medical) justification for the parameters to be sensed and measured. Generally, there are few mining situations where monitoring of heart rate is considered essential, although it could provide a useful indicator in high heat stress situations. There is however a significant body of work which confirms that deep body temperature or core temperature is a measure of fundamental importance when working in hot and humid environments. If individuals are required to undertake demanding exercise in conditions of high heat and humidity, it is possible for body core temperature to rise progressively and reach or exceed safety guidelines (>38.5ºC).

Mining guidance on heat stress monitoring was reviewed. There are currently no physiological heat stress safety limits prescribed for the mining industry, although guidance has been published on precautionary measures and environmental temperature 'action' levels. Guidance has been developed in a number of countries concerning permissible limits for rescue operations, where breathing apparatus is worn in hot microclimates. This includes; Australia, Czech Republic, France, Germany, Poland, RSA, UK and Ukraine (Bresser and Kampmann 2000, DeKlerk 2000, Gaman and Tanasa 2000, Goldstein and Nowak 2001, Smolanov and Klimenko 2001).

Prior to considering sensors and instrumentation, a review of core body temperature measurement and heart rate monitoring was conducted. This included comparison of various body sites and associated measurement accuracy in comparison with ‘gold standard’ clinical methods. Focus was given on the measurement of deep body core temperature, since there is a variety of previous research and anecdotal observation, which confirms that this is the most critical physiological parameter concerning physical activities carried out hot and humid underground mine conditions (Jones et al 2003).

Core body temperature is regulated mainly by the hypothalamus in the brain, which responds to input from thermoreceptors located centrally in the body core and peripherally in the skin. The preferred sites for measuring core body temperature are considered to be those closest to the hypothalamus, the temperature-regulating centre. The temperature in the pulmonary artery, oesophagus and bladder can be monitored to measure core values, but these sites involve invasive thermometry and are not considered practical choices in the current context. Reference is made to reviews of clinical thermometry (Holtzclaw 1998, Klein et al 1993, Milewski et al 1991, Cattaneo et al 2000). Useful guidance is also offered in ISO 9886:2004.

On the basis of medical advice and practical observations, the priority was considered to be the development of a body temperature measurement capability, followed by heart rate monitoring and then possibly to consider the outputs of personal alert safety systems used to monitor thermal exposure (Bryner et al 2005).

During the project, discussions were advanced with Hidalgo, a UK based company, concerning the possible adaptation of their military physiological monitoring system ‘Equivital’. Equivital had many significant attributes that were of interest to the research. The system provides remote physiological monitoring through single self-contained devices that can gather a number of physiological parameters to monitor the health status of an individual. The device is shown below in **Figure 3.3.4-1**. Equivital is designed to operate across a PAN (Personnel Area Network), which is currently either Bluetooth or low power packet radio used by the US Military. The system can also send data in two modes: full disclosure or partial disclosure. Full disclosure sends all of the physiological information back to a central controller, or a local logical device for analysis. In partial disclosure mode the devise uses an on board algorithm to give a welfare indication with the following three classifications: Red – high risk/unsustainable physiology, Yellow – physiology level requiring more detailed analysis, and Green – low risk/normal physiology.

Figure 3.3.4-1: Equivital - remote physiological welfare monitoring system

The different types of physical parameters and features of the Equivital system are given below.

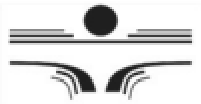
Heart Rate

The QRS detection algorithm used offers performance benefit over a simple R wave detector, which has known vulnerabilities. The SEM conforms to ANSI/AMIEE standard EC13 for Cardiac Monitors and uses a novel two lead ECG measurement to provide high quality Cardiac data.

Respiratory Rate

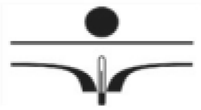
Respiration rate or effort is primarily obtained from the expansion of a belt around the wearer's chest. Future versions of the SEM will also derive respiration rate from ECG measurements and from thoracic impedance measurements.

Motion / Position



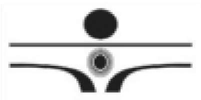
An indication of the wearer's motion is obtained from a motion sensor built into the SEM and is classified into three levels of activity: 'Stationary', 'Low' or 'High' activity. The sensor is also used to detect the wearer's orientation, classified as: 'Upright', 'Prone', 'Supine', 'Inverted' or 'Side'.

Temp



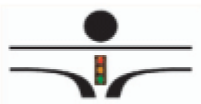
Skin temperature of the wearer’s chest is measured by a clinical grade thermistor. This temperature is included in a calculation of the wearer’s activity status to derive a measure of predicted thermal strain.

Impact Detection



The motion sensor in the SEM can detect potentially harmful movements that could have been caused by heavy impacts and falls.

Welfare Indication



The parameters described above are correlated together in context with each other according to a proprietary algorithm in order to form a Physiological Welfare Indicator, providing a measure of the wearer's primary cardio-respiratory status and supplemental information on the user's thermal, neurological and activity status.

This type of physiological welfare monitoring system was considered to be very suitable for transmitting across a LR-WPAN (low rate wireless personal area network), particularly using the welfare indication mode where most of the processing is done locally by the device itself. However, there could also be a requirement for a higher bandwidth upload, either periodically or upon a warning indicator. This could be achieved by having dedicated zones with an alternative wireless system (e.g. Bluetooth, WiFi) where the individual either has to pass through at certain times of the day or has to go (or be taken) to upon the device issuing a warning indicator. This application has the potential to combine into an overall safety and tracking monitoring system.

As alternative to the above system and having into account the information obtained from the researches performed on the existing products on the market, a prototype of heart rate sensor suitable for mining application was successfully developed. Heart rate measurement principle employed in the sensor is based on processing of the ECG signal picked up by two chest belt electrodes. Dominant peak of the ECG signal (R wave from QRS complex) is processed by specialised ASIC. The output from signal conditioning ASIC is further processed by a microcontroller and then measured heart rate values are transmitted with use of ultra low power ISM transceiver. The block diagram of the device is depicted in **Figure 3.3.4-2**.

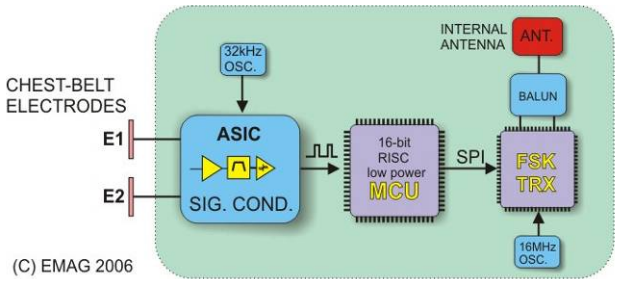


Figure 3.3.4-2: Heart rate sensor – main functional blocks

The final revision operates with the communication protocols developed in **tasks T4.3 and T4.5**. The software was also enhanced by advanced signal filtering in time domain. Also the power consumption was reduced by using low power transmission schemes (derived from results of T4.3/5) and employing power saving modes of ultra low power microcontroller.

The final revision of the sensor type 'HRM-1' was manufactured for purpose of underground trials in WP5 (see **Figure 3.3.4-3**). After positive results of underground trials it was subjected to tests performed in accredited medical laboratory ITAM Zabrze. These tests proved its conformance with medical standard IEC 60601-2-27:2005.

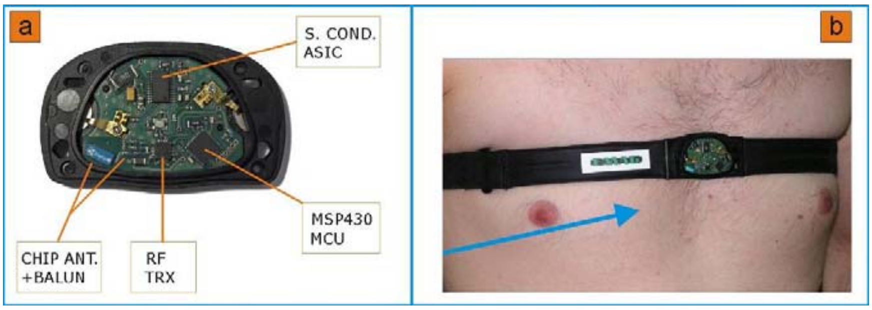


Figure 3.3.4-3: Heart rate sensor – final revision

The sensor measures following parameters:

- heart rate (25-240 BPM)
- temperature (0-60^{o}C)
- battery voltage (10bit resolution)

For purpose of the tests also special revision of the sensor hub was developed. It was based on TRX-NRF1 module developed in course of **tasks T4.3&T4.5** and was equipped with LCD display (see **Figure 3.3.4-4**) which enabled visualisation of the measurements in real time. The HRM-1 sensor has been designed with all good engineering practice to comply with ATEX requirements. The certification process will be carried out in course of internal project during the commercialisation phase.

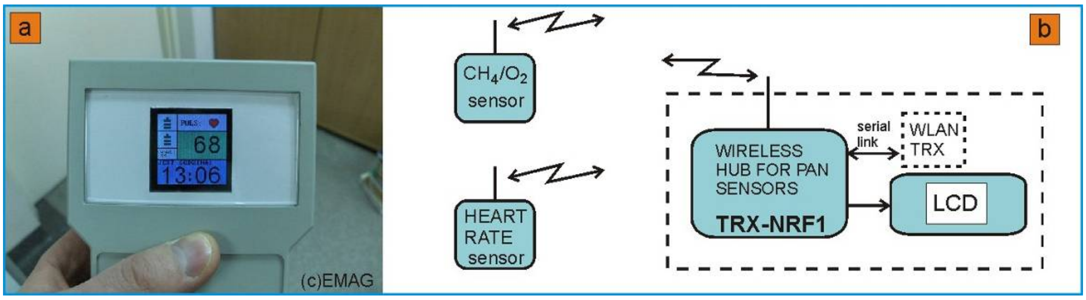


Figure 3.3.4-4: Sensor hub used for testing of the sensors

This is expected to be undertaken shortly because of commercial interest from Polish mining entities namely central mining rescue station - CSRG and Polish coal producer - K.W.S.A.

The primary application for the developed sensor will be monitoring of physiological conditions of rescue team members during the rescue action. The sensor also can be used day-to-day for monitoring of health status of underground workers in severe climatic conditions. Final product will consist of the HRM-1 sensor and wrist watch type readout unit (currently under development). – being miniature version of the sensor hub. The product will be introduced to the market as soon as relevant certificates are obtained.

Personal weareable audio transducers

In the wireless m-Comm application, aimed as voice link interface for the forward rescue team member(s), the primary interfaces are audio and a push-to-talk button. There were a number of simulated tests and operational discussions with UK mines rescue staff regarding the ergonomics and operational experience of microphones and earpieces in an underground environment. Comfort and convenience to the wearer/user is very important otherwise the equipment may not be properly deployed and hence safety could be compromised. Of the number of audio interface devices examined the throat microphone, had been the proposed as the best solution to gaining interference free voice communications with a fully kitted rescue person.

However, the Mines Rescue Services' experience of wearing such an arrangement in high heat and humidity was that it resulted in the wearer suffering neck rash after a period of time. As a consequence, prototype wireless units were fitted with alternative plug-in options, such as, directional microphones strategically placed on the face mask, ear-microphone etc. There are also options available for noise cancelling circuitry imparted in a specialist codec chip (part of the Bluetooth interface circuitry). The User Feedback Section of 4.4 summaries the end-of-project solution to this much researched Task.

3.3.4.2 Smart personal sensors for environmental values (Activities Task 4.2)

For the purpose of environmental parameters monitoring, a miniature wireless sensor set was developed. First 'wired' prototypes were developed in third semester of the project and were able to measure levels of CH_4 and O_2. The CH_4 sensor was developed to meet low power consumption requirements enabling operation in battery powered equipment. To reduce power consumption only one Wheatstone bridge was employed (with one sensitive and one non-sensitive pellistors). It measures CH_4 in low concentration area (up to 5%). Higher levels are detected by measuring value of oxygen (using principle that CH_4 replaces oxygen from air mixture). To further reduce power consumption time sliced operation was implemented. The oxygen sensor which was used is electrochemical cell type requiring no energy for its operation. Calibration and compensation procedures were simplified because sensor outputs are processed by mixed signal microcontroller using embedded programmable gain amplifier, precise analogue to digital converter and offset compensation by means of integrated digital to analogue converter. The measurement data is then transmitted to wireless transceiver via serial interface.

In final revision of the sensor set (see **Figure 3.3.4-5**) a few improvements were introduced. It contains carbon monoxide sensor because measurement of CO level was found essential for wearable hazard detection device. Secondly, it is equipped with a temperature sensor, based on SHT-7 device, for compensation of gas sensing elements. This additionally enables measurement of climatic conditions i.e. temperature and relative humidity.

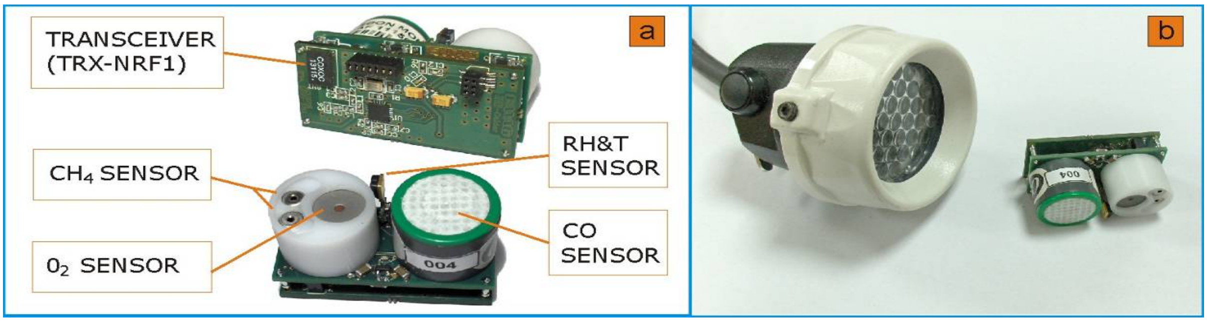


Figure 3.3.4-5: Wireless environmental sensor set

With regard to radio transmission the sensor set was integrated with the TRX-NRF1 module developed in course of T4.3&T4.5. The transceiver is programmed with end-device software to enable operation with the other components (HRM-1 and sensor HUB) within the PAN network.

Measurement accuracy and cross sensitivity was verified in specialised laboratory and was found to be sufficient for a wearable hazard detection device. The sensor set is small enough (see **Figure 3.3.4-6**) to be integrated with headpiece of a cap lamp. It can also be assembled (with a battery) as stand-alone wearable device not bigger than a pack of cigars.

Discussions with representatives of cap lamp manufacturers indicate there would be a chance to commercialise the sensor set as embedded element of a cap lamp – but at the moment economical factors make it problematic at least for day-to-day operating equipment. Practical evaluation of applicability of the sensor set for assessment of environmental conditions in safe havens and during the rescue operations is envisaged within RFC-PR-07016 project EMTECH (Mine Emergency Support Technologies).

Another option for environmental parameters monitoring is the use of the abovementioned m-Comm wireless system. It is also designed to accommodate data channels to monitor the environment and the physiology of team members during rescue operations. With the collaboration of various partners involved on the project and general understanding of what is possible to monitor, the prototype m-Comm wireless system was designed to include analogue interfaces for a number of transponders or sensors.

Given the bandwidth restriction of the guided wire section of the m-Comm, which can be likened to a one way telephone line, a 'silent' in-band data transmission method was devised; see section T4.4 for design, trials and improvement cycle details. The data traffic will be time labelled, source identity coded and, initially, limited to three data channels. Team members' mobile unit will act as the source point for monitoring and automatically up-loading data. Typical data channels would be body or ambient temperature, methane gas concentration and humidity. Sensors are commercially available and, where necessary, can be modified to be compatible with operational requirements of the wearer, ATEX and the m-Comm wireless interface.

3.3.4.3 Integration of personnel voice communication (Activities Task 4.3)

Part of this task activities were focused on development of interface between the personal wearable sensors and intrinsically safe wireless communication headset. For that purpose, software and hardware modifications of communication headset type UNO-01 which was in preliminary prototype stage, were carried out.

The UNO-01 headset combines hearing protectors and short range 2.4GHz digital radio transceiver (**Figure 3.3.4-6**). It is targeted at day to day operation in mines and has all necessary functionality such as noise cancelling and environment over-hearing with spatial sound positioning.

Figure 3.3.4-6: Prototype UNO-01/TH1 communication headset

The introduced modifications made possible following functionality:

- reception of data from personal area network sensors,
- optional voice gateway functionality (with PAN-WLAN gateway see task T4.5),
- indication of low battery/malfunction status of PAN sensors.

First of the features enables triggering of pre-recorded voice alarms/warnings whenever safety thresholds of values measured by PAN sensors are exceeded. By such mechanism the exposed person can be immediately and effectively informed about the danger. To achieve abovementioned features the electronic module of the UNO-01/TH1 headset have been integrated with the final revision of sensor hub module TRX-NRF1 and the appropriate interface software have been developed.

The TRX-NRF1 module was developed to achieve performance tailored to PAN applications. Its hardware was designed to be universal and module can be either a hub or end device depending on software. The hardware is based on ultra low power components to achieve maximum battery conservation. The device uses proprietary communication protocol which has an advantage over standard based ZigBee or Bluetooth that it needs very low memory and computational resources. As result the power consumption and latencies related to protocol handling are substantially smaller. The developed communication firmware was successfully tested in laboratory and underground tests during WP5. It enables operation up to six slave devices and uses frequency hoping scheme enabling simultaneous un-interfered operation of multiple PAN networks. The device is powered from 3.3V power supply. Communication with host device which can be the headset, sensor set or WLAN module is done via low voltage serial interface.

Optional communication of the headset with WLAN infrastructure is established with use of PAN to WLAN gateway developed on task 4.5. The headset operates as a master device to PAN sensor network in order to safeguard safety related functions. Communication with personal area sensors has priority over communication with WLAN gateway. Retransmission of sensor data to WLAN network is done trough supplementary data channel from the headset (see **Figure 3.3.4-7**).

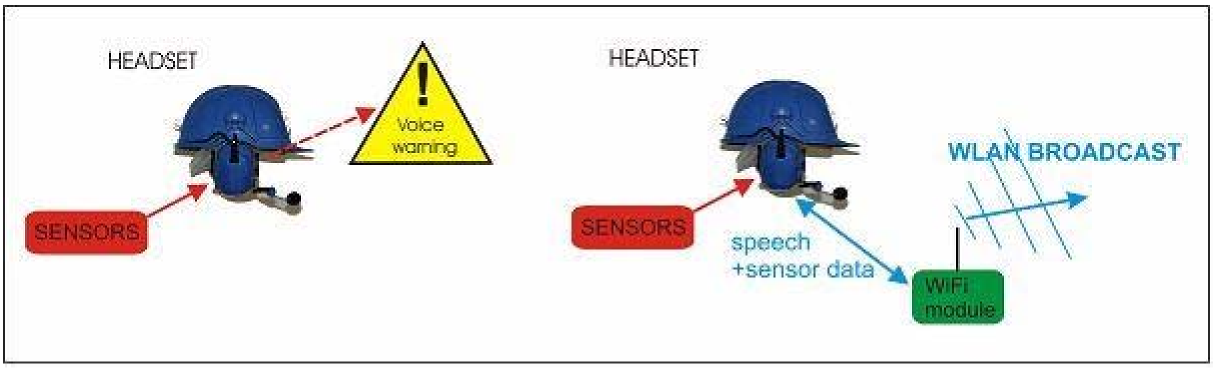


Figure 3.3.4-7: Digital data paths for voice and sensor data

Abovementioned functionality was successfully introduced to the UNO-01 headset at preliminary prototype stage prior to its ATEX certification. The UNO-01 device was first shown to the public during the 21st World Mining Expo and Congress (September 2008) with very positive feedback. The

Product is currently being introduced to mining market by company Telvis.

In addition to the above and as a practical application of the integration of wireless voice devices into mining headsets, a voice communication + PAN data transmission system between miners in general and the operators of dangerous machines in particular, and the mine data transmission backbone using wireless autonomous devices has been developed, as a continuation and extension of the work carried out under the RFC-CR-03003 project.

The system consists of a wireless remote control system for shearers, which transmit both voice and data information to the control upper gate of the shearer, and for another part, a high quality voice system, using digital processing techniques, plus advanced data acquisition control units, to be integrated in high speed monitoring networks (refer to RFC-CR-03003 technical reports for further details).

The work undertaken under RAINOW consists of adding wireless connectivity capabilities to the voice amplifiers that were developed under RFC-CR-03003 (reported on **task 4.5**). The integration of the voice and data wireless transmission system in the general control and monitoring network allows, in addition to personal telemetry, personal voice communication in the network. People operating any kind of machinery are connected to a voice system for both emergency and normal operation.

For this purpose, a specific interface has been developed, that connects PAN network, including voice communication, to the voice amplifiers developed under the above mentioned project. For this purpose, it was added a Bluetooth module to the amplifiers, which are being modified -both in software and hardware- for including new data and voice paths.

Analisys of interferences between different systems

The developed wireless m-Comm emergency rescue communications system is designed to be a stand alone system and as such its integration into mines' fixed wireless systems is limited to emergency interoperability and mutual interference issues only. The paramount consideration for the m-Comm wireless system is its continuous operation in adverse conditions following an incident underground and along side any mine wireless system even in a damaged state. Hence the initial testing, under Task 3.6, to asses the degree of interference between the various RAINOW proposed wireless communications systems. In order to assess the co-existence of the whole wireless m-Comm system in realistic underground situations, the m-Comm's wire guided section had been subjected to numerous underground operational exercises and could be claimed to be immune from any wireless or radio interference. However, there have been instances where power cables and transformers have caused a breakthrough of interference in the form of voice channel background noise. Whilst the level of noise has not stopped communications in the past it is nevertheless distracting. In a system with an extended wireless link the un-muted noise would be extend to the forward team member causing more than a distraction. The forward team member will be expected to wear an earpiece, or similar, at all times and the presence of loud irritating noise would inevitably lead to the system being either switched off or removed. More importantly, the un-muting action would result in the loss of the up-link control. The research and evaluation work required to overcome this specific interference problem is described under Task 4.4.

Bluetooth Wireless

The pragmatic solution for a mines rescue communication wireless link was to use one of the latest and readily available Bluetooth single chip audio configured (Free2move) wireless module. This candidate wireless technology based on the CSR range of Bluetooth Class II chips and fully FCC, CE and IC compliant is remarkably effective in maintaining communications within confined spaces, as reported under Task 1.3 and 5.1.

In order to maintain future security of wireless m-Comm systems to the same level as tested to date the basic design had to incorporate flexibility to be adaptable to future change. Mines may employ newer and more powerful radio systems that are incompatible with current Bluetooth devices or the next generation of wireless devices may be very different from the present versions, i.e., beyond the range of tests made during the period of this project. By incorporating a dedicated electronics interface section between the wireless module and the m-Comm electronic circuitry up-grading or even the possibly incorporation of different wireless technology/modules would be made easier. This also leaves open the possibility for employing UWB technology, see below. There are indications that UWB devices with Bluetooth protocol are likely to be marketed shortly. As was reported in Task 1.2, UWB is a prime technology for wireless mines rescue communications. The examination and trials of a candidate UWB wireless system are therefore reported below.

UltraWide Band Technology

In parallel with the implementation of the Bluetooth solution (proof of concept), work continued with the evaluation of UWB technology. In mining application the UWB technology would seem the best solution from the technology selection research under Task 1.2. It was viewed as the most obvious choice for an emergency wireless technology particularly for its total independence from other mine wireless systems and its (EM wave) reflection tolerant behaviour.

UWB technology is widely exploited in ground and through-wall radar applications and is only now finding favour in communications applications. Interestingly, it is its ability to overcome multi-path problems within office and home environments, the problem that limits current wireless gate way systems' data transfer speeds. Multi-path causes inter-digital (bit) smearing when the timing of reflective wave and the direct wave coincides with bit length time. Since UWB takes the strongest pulse and ignores the rest the data rate can be increased by a factor of 10 or possibly 100. This is the driving force behind the recent upsurge in development of UWB technology.

UWB or pulse radio is different to conventional radio in that its narrow band receiver circuitry is replaced by time domain coherence receiver. UWB transmits a repetitive high pulse and receives or sums the pulses in a time frame hence its ability to deal with multi-path signals and calculate distance from transmitter to receiver, see **Figure 3.3.4-8**. If the sub-micron wide pulse is viewed in the frequency domain it would have a very wide and flat spectrum. This is the complete opposite to the conventional narrow band radio which we are more familiar with.

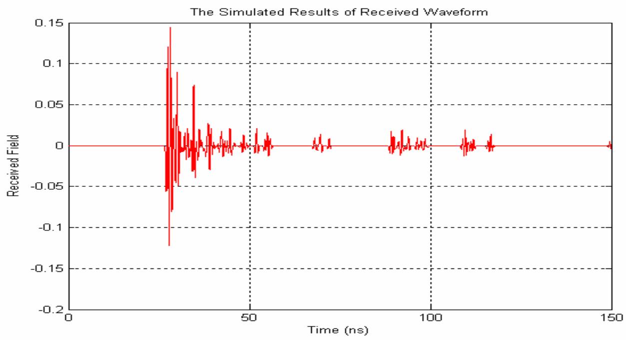


Figure 3.3.4-8: Example of a received pulse signal with secondary pulses representing multi-path (time delayed) signals

The potential of an UWB system was examined using the PulsON 200 evaluation kit from Time Domain Inc., see **Figures 3.3.4-9 and 3.3.4-10**. Its function determining software was configured to demonstrate and evaluate: a) distance against data throughput, b) distance measurement between two UWB devices and, c) angle of arrival of signal, i.e., direction. UWB technology was selected as the best solution, on paper, to overcome multi-path propagation in tunnel and confined spaces. As reported in numerous publications, there were no apparent interference between the pulse radio system and the conventional 2.4GHz wireless systems. The PulsOn radio system used was very low power and only had a range of about 20 m. The susceptibility of the PulsON radio's input stage to being saturated, or swamped, by Bluetooth transmission was higher than expected.

As matter of general interest, Time Domain Inc., also produce an active RFID tracking system. The wrist tag has a battery life of 4 years and has a line of sight range of 75 m, see inset below, **Figure 3.3.4-11**. Receivers placed at strategic locations can provide information to a software package which reproduces an up to the minute 2D picture of the tag locations within its range. As was reported above, UWB technology provides automatic distance (from transmitter to receiver) and enables accurate location information even within buildings. The Tag is a UWB transmit-only device that sends out very short packets at predetermined transmission rates. These very short packets (less than 100 microseconds) allows for several thousand tags to be tracked in the same area. The data in the tag packet includes the tags ID, a packet number, battery status, and a received signal strength indicator.

Figure 3.3.4-9: UltraWide Band (PulsON 200) evaluation kit, transmitter/receiver unit with external anntena (seen in green to the left of photograph)

Figure 3.3.4-10: UltraWide Band (PulsON 200) evaluation kit undergoing distance measurements tests

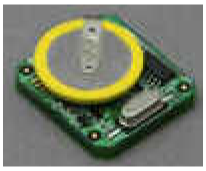


Figure 3.3.4-11: UltraWide Band PulsON P350 Tag information

3.3.4.4 Wireless adapting of mine rescue communication systems for hands-free operation (Activities Task 4.4)

Wireless Technology Options for Mines Rescue Communications

The programme for evaluation and integrating wireless devices into mines rescue communications system was technically complex and key to the successful outcome of the main aims of the RAINOW Project. This section reports on whole system failure analysis as well as fabrication of prototype wireless m-Comm units. The field evaluation of the prototype(s) wireless m-Comm units are reported under Task 5.1.

Reliability and Fabrication Considerations

A simplified summary of the main reliability concerns of each sub-part or function of the wireless m-Comm system is depicted below, see ***Figure 3.3.4-12 and Table 3.3.4-1***. This systematic approach to failure analysis highlights potential reliability weaknesses and assesses their relative importance within the whole system. Examples from the listed concerns are further discussed together with counter measures. It should be noted that this is not a full listing of the failure analysis nor is it a full report of the techniques employed to ensure the highest reliability, within practical limits, is achieved for the wireless m-Comm system.

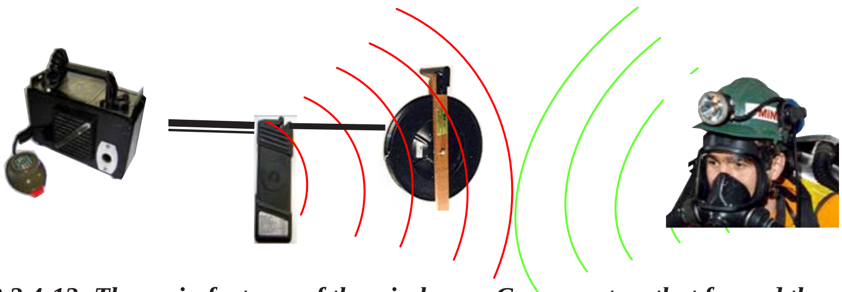


Figure 3.3.4-12: The main features of the wireless m-Comm system that formed the reliability review.

BASE UNIT	GUIDE WIRE	HANDSET/HUB	WIRELESS LINK	WIRELESS UNIT(S)
Power	Breakages	Power	Out of range	Power
Operations	EM noise	Operations	Drop-outs	Operations
Equipment	Fire damage	Equipment Malfunction	Interference	Equipment damage Physical damage

Table 3.3.4-1: The main features of the wireless m-Comm system that formed the reliability review

Each of these highlighted reliability issues are expanded below, in order of most important.

Power

Repeated concern about reliable power supply underlines the fundamental importance of a single power source. Wireless m-Comm adopted a conventional but well proven Ni-MH rechargeable technology. The requirement for ATEX approvals also favoured Ni-MH cell technology.

EM noise

The conventional squelch control for the m-Comm system had always been problematic and a number of modifications had previously been added to overcome total loss of communications in the event of co-channel (EM) noise or very low carrier signal, including the introduction of adjustable control for the base station. However with the 'through' control into the wireless section any possibility of the channel locking on due to electromagnetic noise would be unacceptable, the system would fail to an unsafe mode. Positive mute control was therefore the only option. This also reduces the need for any operator intervention or adjustments. Positive control is achieved by sending a sub-audio tone to the receiver's muting circuit over the same signal path as the audio. Whilst this tone control muting has superior performance it does require embedded processor control to arrange the delay between the mute tone and the carrier signal otherwise the operators are subjected to unexpected noises at the end of transmission. Conventional two-way radios use a standard multiple sub-audio tone generator and detector chip which is ideally suitable for the m-Comm modification, termed 'continuous tone controlled squelch system' or CTCSS for short. The CML manufactured FX 456 chip was used throughout in the manufacture of the wireless m-Comm system prototype.

Operational

Analysis indicated potential system malfunctions that could be caused by an inattentive operator or under pressure. These range from the simple action of not releasing the press-to-talk (PTT) button to wondering out of wireless signal range. Major system failure modes, such as the one caused by the unreleased PTT button are best corrected or overridden, after a delay, by the embedded PIC processor/controller. All these extra control and protection features increase the dependence on a single processor and the integrity of its embedded software.

With Bluetooth wireless modules there is no simple warning system for the out-of-range problem.

Embedded software

The introduction of an internal processor for each wireless m-Comm system could potentially reduce the overall reliability. In order to maintain and if possible improve the reliability of each unit and consequently the overall system special attention had to be given to both hardware and the embedded software. Consideration for reliable hardware is given in the next sub-section. Software reliability is difficult even to quantify. There is little helpful documentation on the subject. Recognising this, good practice was adopted from a range of control software expertises including nuclear power station experiences. It is fortunate that the wireless m-Comm embedded software is relatively small ranging from 40 to 400 lines of machine code. This makes it possible to program in machine code and to segment the program. In addition, the use of 'interrupt' input signals was ruled out in order to control or reduce any timing criticalities. Auto reset actions were added on each operation sequence or cycle and as a further precaution the reset point alternated to different points in the program flow chart. Low voltage detection ensured no processor operated below a critical voltage limit. Further precautions were taken to filter the processor's input and output signal and terminate any un-used terminals.

Hardware

The rigorous design and manufacturing procedure for products destined for mining applications were applied throughout. These included: minimise the number of mechanical components, such as, switches, plugs/sockets, etc., reduce mechanical and electrical stress factors, protect against environment and corrosion and minimise external impact damage.

Equipment used for emergency rescue is subject to a high level of physical damage. The rescue team members as preoccupied with saving lives and the equipment they employ must function intuitively. It was in this regard that the project encountered its greatest challenge. The design of the wireless m-Comm had to be small, light weight, with comfortable earpiece/microphone and simple to operate. Since interpretation of “comfortable” and “simple to operate” is subjective the prototype rescue mobile wireless unit has the option to change the type of earpiece and/or microphone as well as its location on the wearer. The wearers will be able to select the most effective interface option for them.

Logistics of Wireless and m-Comm Interoperability

The method of checking the interaction of all possible combinations of the wireless link and the m-Comm system in its many combinations involved laborious tabulation of each option. Each sheet showed the signal path and control logic for each particular mode of operation, e.g., forward team member talking through the handheld ‘hub’ to the base station, hub to forward unit, hub to base, and so on. The exercise also provided a logical approach to setting priority in the restricted (one way) communication path through the wire guided section of the m-Comm system.

The Progressive Stages of the Prototype Handheld (Hub)

Laboratory testing of the prototype wireless mines rescue communications system initiated a number of minor design changes. The Base and Handheld units are based on a common design and PCB layout. The reel hub option is yet another packaging on the same design.

The prototype wireless m-Comm unit was designed and fabricated to have a segregated wireless unit with a standardised interface. A systematic failure analysis of the overall wireless m-Comm system resulted in a number of modification to the basic m-Comm system as well as many design safeguards. **Figure 3.3.4-13** shows the first stage necessary for the m-Comm system to have a ‘continuous tone controlled squelch system’, CTCSS, and an electrical interface to control the ‘press-to-talk’ function.

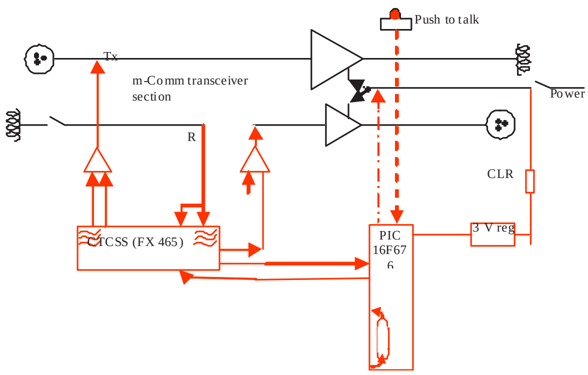


Figure 3.3.4-13: Schematic diagram of the m-Comm configuration with added circuitry necessary for CTCSS and wireless interface

Figure 3.3.4-14 below shows the added wireless Bluetooth module interface to the modified m-Comm transceiver section. In this version the data from the forward wireless unit was transmitted at the end of each voice transmission to base, as a false ‘roger’ bleep. In tests, the scheme proved difficult to operate reliably mainly because the capture of the data stream required longer than 300 mSec. However 300 mSec ‘bleep’ was the absolute maximum acceptable period within a voice channel.

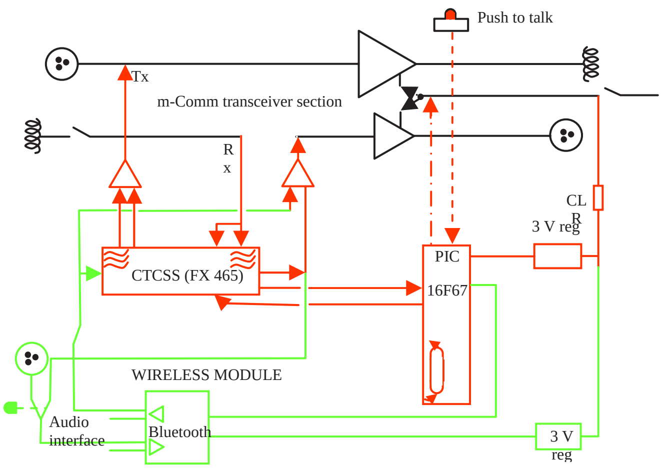


Figure 3.3.4-14: Modified m-Comm schematic with wireless module. The external wireless module is connected via a common (Bluetooth) interface

Given the problems of short burst data transmission within the audio channel a revised method had to be devised. Recognising that the CTCSS chip could be used to create more than one discrete channel along the m-Comm link a revised scheme was developed allowing data to flow up the m-Comm link 'silently' and in-between voice transmission. The FX 465 chip can be dynamically reconfigured for different tones thus enabling the one m-Comm channel to be used for two (or more) different destinations. The revised signal/data and control connections are shown in **Figure 3.3.4-15**, below. It is noted that this latest version is operationally less restricted and requires no added circuit components. The base station arrangement is essentially the same as the handheld except for the extra CTCSS chip to output the data.

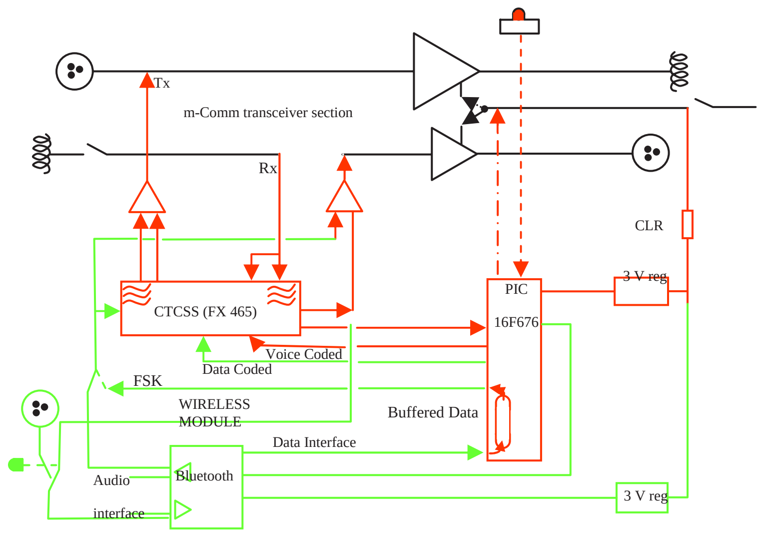


Figure 3.3.4-15: Latest version of the wireless m-Comm with the data interlacing option

User Feedback

The human interface of the forward wireless unit is seen as crucial in achieving an acceptable and reliable system. There has to be comfortable microphone/earphone, accessible press-to-talk (to base) button and, at some stage, physiological and environmental sensors all connected to a small battery powered wireless unit. The culmination of extensive evaluation trials narrowed the preferred options down to: combined internal earphone and microphone, separate pluggable earphones and throat microphones or an earphone with clippable microphone. All are robust and made to industrial or military specification. Location and action of the press-to-talk button is again a personal choice but must not be accidentally switched on by the wearer when, for example, squeezing through narrow openings, etc. Weight and restriction of movement of the wearer's head is also a major consideration. The evaluation of audio sensors and the ergonomics of the wearer's wireless units is presented in **Task 5.1.**

3.3.4.5 Development of a personal communication interface for WLAN access (Activities Task 4.5)

The work developed on this task is based on two different technologies; Bluetooth and WiFi.

Roadway amplifier with Bluetooth connectivity

A roadway amplifier including wireless voice communication base on Bluetooth was developed. It is compatible with fixed systems, so that a global voice communication is possible through the entire mine, from both traditional wired voice amplifiers and from wireless devices.

In that sense, a redesign of the roadway amplifiers developed under RFC-CR-03003 project has been carried out, in order to add a wireless data and voice communication interface to the equipment. The device (**Figure 3.3.4-16**) is connected to a field-bus based system, and provides Bluetooth coverage to an area around it, from where a voice communication can be started using wireless devices.

The major changes have been:

- The control software is executed by a dSPIC33F family device.
- A Bluetooth Class One module has been added to the device, based on Blueradios® modules. This will allow both wired and wireless voice transmission on the same device. In addition to the wired voice transmission, the roadway amplifier will provide a coverage area around it (the target range will be determined during field tests) that will allow the establishment of a communication using a Bluetooth headset.
- The addition both a dynamic battery charger and a high precision current integrator provide a more efficient use of the energy resources available in the field-bus, charging the battery with the remaining current capabilities of the power supply and stopping the input consumption when the battery is full.
- Some mechanical modifications also have been done, especially for improving the removable battery pack guides and enhancing the battery to equipment connector.

Figure 3.3.4-16: Enhanced roadway amplifier including Bluetooth

Field test performed on real mine longwall are reported in WP5. Currently the ATEX certification process is being performed by LOM notified body.

Communication interface for WLAN access

Regarding to WiFi technology, part of the activities was focused on interconnection of wireless Personal Area Network to Wireless Local Area Network. For that purpose a prototype gateway device was developed. It consists of personal area network hub and embedded WLAN transceiver module. The hub device is based on low power TRX-NRF1 transceiver module (described in T4.3) which enables connection up to six slave devices operating in PAN network. The Wireless LAN module is based on low power WLAN transceiver which was chosen as result of market search followed by laboratory performance tests. The transceiver module is based on low power 802.11b/g radio chipset and ARM7 32-bit RISC microcontroller

During the tests the WLAN module was connected to WLAN infrastructure network operating in Wireless Distribution System configuration. The data throughput sustained and burst were measured and found sufficient for gateway application. After the connectivity performance was positively verified interfacing, power supply, and protection circuits were developed to be finally integrated in a compact (60x40x16mm) module dubbed ‘TRX-WISM’. Its basic electrical characteristics are as follow:

- power supply voltage: 3-6V;
- power consumption (max. 0.8W).
- sustained data rate: 250kbps.
- burst data rate: up to 921,6 kbps.
- RF output power +15dBm (maximum).
- antenna diversity (embedded antenna and connector for external aerial).

To operate as PAN to WLAN gateway TRX-WISM module was connected to TRX-NRF1 via low voltage serial interface (see **Figure 3.3.4-17**). To enable desired functionality dedicated revisions of test software for both modules, enabling configuration and interconnection, were developed.

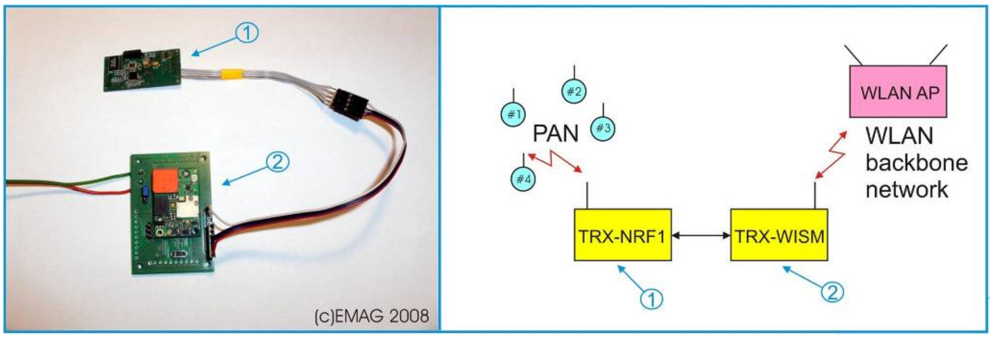


Figure 3.3.4-17: Prototype PAN and WLAN interconnection gateway

Performance tests of the gateway were repeated during WP5 activities and proved reliable operation of the device also in underground conditions.

Finally, a wireless module being modified revision of TRX-WISM was subjected to ATEX practicality verification in OBAC notified body and get positive opinion in April 2008. This was done as part of activities within EMAG’s internal project.

3.3.4.6 Personnel tracking and guidance in critical situations (Activities Task 4.6)

Concerning the development of personal tracking and guidance capabilities for use in critical (emergency) situations, the legislative developments elsewhere (mainly the United States) were reviewed, which are anticipated to affect how these systems should be specified and possibly commissioned, tested and used. Whilst similar legislation is not anticipated in the European Union or candidate Accession States, it does nevertheless represent useful information towards defining cardinal point specifications and approved codes of practice for these technologies/ requirements.

Two primary sources are noted:

1. The US *Mine Improvement and New Emergency Response Act* of 2006 (otherwise known as the MINER Act 2006), together with Programme Policy Letter(s) issued by the US Dept. of Labor Mine Safety and Health Administration (MSHA). Specifically, section 2 of the MINER Act deals with emergency response and the requirement for post-accident tracking and communications.
2. The Report on *Mine Safety Recommendations* made in response to the Sago and Aracoma disasters in the United States, and undertaken by the West Virginia Mine Safety Technology Task Force.

Development of Underground Tracking System

A ‘Zonal Location Tracking’ system was developed using EmberZNet, which is a ZigBee ratified mesh wireless networking technology. An overview of the system is shown below in **Figure 3.3.4-18**. The ZigBee router (ZR) devices are pre-installed in known locations and separated at a nominal distance of between 50 and 100m. In order to overcome a data ‘bottleneck’ in large networks, every sixth ZR device can need to be configured as a gateway (GW) to send data to the host network e.g. back bone

Ethernet infrastructure. The intention of limiting the GW spacing to 6 devices is to limit the information being sent to 6 hops. Mobile End Devices (MED) are attached to personnel and/or vehicles / mobile plant. These are allowed to temporarily join with a ZR node and then once data exchange has taken place leave the network until a new ZR node is found. As a MED travels around the mine it can be tracked in zones defined by the physical location of each ZR. There is scope to extend this application to incorporate other data telemetry, for example, vital signs information of each mine worker, environmental monitoring or on board machine diagnostics.

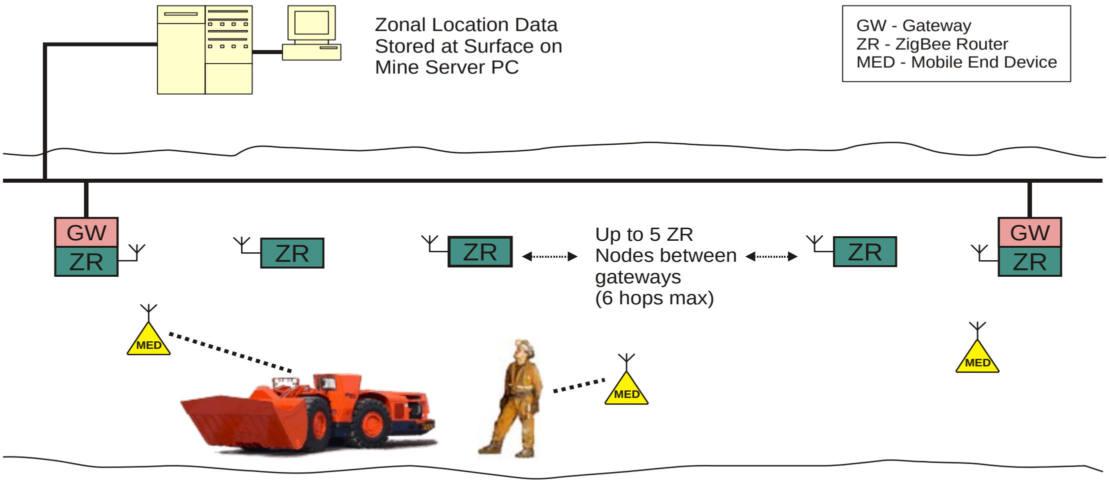


Figure 3.3.4-18: Zonal Location Tracking System using EmberZNet

Underground Tracking System Hardware

In order to carry out a large scale wireless mesh network demonstration (>30 nodes) some 40 tracking system devices were assembled. The ZR and MD devices utilised ETRX2 modules and daughter development boards. For environmental protection they were enclosed in IP67 enclosures with IP67 operating switches, and were powered using hybrid NiMH AA battery packs. **Figure 3.3.4-19** below, shows the MD (mobile device) and ZR (ZigBee Router) devices including the ZRs installed *in situ* at the CSM Test Mine in Cornwall, UK. The gateway device comprises a Telegesis EAP-E ZigBee to Ethernet Router device, acting as a bridge between the EmberZNet (ZigBee) network and Ethernet backbone.

Figure 3.3.4-19: Underground Tracking System – ZR and MD nodes

An enhanced portable and personnel device based on ZigBee wireless technology was also developed. It is aimed to be part of the wearable equipment of the underground personnel.

The main functions of these portable devices are the following:

- Alert the personnel in case of emergency and provide information about it (focus location, type of disaster, etc.).
- Show a safe route up to the nearest refuge or way out.
- Inform to the network and global control system about the person location.
- Send information on the state of the person (orientation and movements) to the global system in order to predict any potential risk.

This new design contains the next elements:

- 16-bits DSP Microcontroller dsPIC30F6014A: Made by Microchip, the same model is also used in previously designed (during WP2) SENSI-C and SENSI-S boards, making easier the software development.
- Digital Compass: The Honeywell HMC-6352 is a complete digital compass solution with I2C connection with the DSP microcontroller.
- 3 axes accelerometer: The model ADXL330 (Analog Devices) gives out 3 analogical signals proportional to the acceleration of the IC in each one of the 3 axes (XYZ). The signals are sampled and digitalized by the microcontroller.
- Graphical display: A 128x64 pixels transflective screen shows the guidance and information to the user. It is a backlighted by white low power LEDs to allow the visualization both in dark and lighted environments.

The next picture shows the fist prototype of the tracking and guidance portable device (**Figure 3.3.4-20**).

***Figure 3.3.4-20*: Final aspect of the portable tracking and guidance prototype device**

Underground Tracking System Software

An overview of the ‘zonal tracking system functionality is shown in **Figure 3.3.4-18**. The system, in terms of the software, comprises a ZigBee network running the Ember EM250 radio modules (ETRX2 devices) as discussed, and EmberZNet software stack, a server hosting an SQL database, and a GUI display providing a visual representation of the data. An overview of the original proposed ZigBee network based underground tracking application was shown in **Figure 3.3.4-18**. This system incorporates the concept using ZigBee router (ZR) devices installed in predetermined ‘zones’ collecting location data from mobile ZigBee devices travelling around within the network. The location data being collected by each of the ZR devices is forwarded to GW (gateway devices), which in turn forwards the information to an SQL database (**Figure 3.3.4-21**).

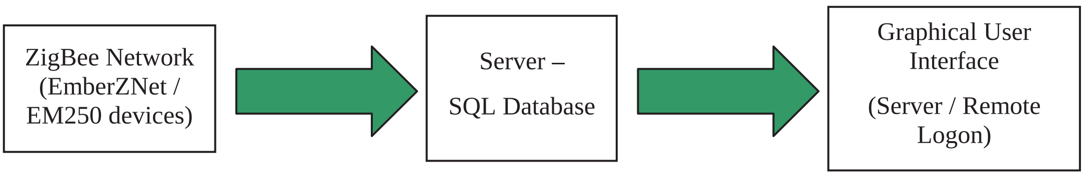


Figure 3.3.4-21: Zonal Location Tracking System Functionality Overview

The graphical user interface (GUI) display is shown below in **Figure 3.3.4-22**. Each ‘Zone’ shown actually represents a ZR device. The MDs (mobile devices) are represented by a simple dot, however, the system provides more detailed information about each individual upon request. The information collected from the GW devices is time-stamped and updated in the SQL database. The GUI is designed to continually update providing a real-time representation of the mine. Underlying the GUI application is the database information itself, which is probably the most valuable after any major emergency incident. In the event of software/network failure the latest or ‘last known’ information is logged on the server. Practical measures would of course need to be taken to back up the server, in the event of server failure.

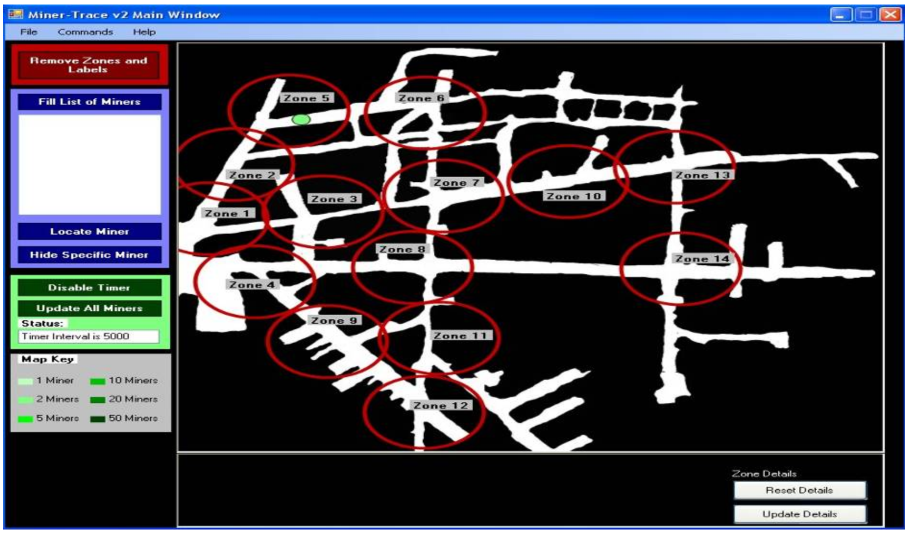


Figure 3.3.4-22: ZigBee Tracking System – Graphical User Interface (GUI)

Enhancing the location system accuracy

According to the above information, the system is based on a distribution of ZigBee routers pre-installed in known locations, and separated at a nominal distance of between 50 and 100 m. This will offer location accuracy equal to the distance between routers. If a bigger accuracy is needed, the distance between ZigBee routers must be decreased, increasing the cost of the installation, unless some means for improving that accuracy is implemented.

Further researches have been performed for finding out the way to predict the distance from a sensor node to its server router using the information related to the receiver signal in one of the devices. Due to the ZigBee router knows all the devices connected to it, the router can perform a device-by-device polling not only to get data from them, but also to know the Received Signal Strength (RSS) from each one and consequently to calculate the distance to the device. This way, the distance between routers could be increased, reducing the cost of the installation, without loosing accuracy (or ever getting a better distance accuracy).

Field data acquisition was carried out thanks to the cooperation of the E.L. Laciana, belonging to the “Fundación Santa Bárbara”, at a Miners Training Mine located in Villablino (León, Spain). The objective of the tests was to find out a propagation model to be applied for ZigBee 2.4 GHz in-roadway propagation.

Measurements were done with distance steps of 5 meters, from the position of the network coordinator to the end of RF coverage in two zones with different topology: straight and curved. The devices used for tests were an evaluation Kit from Telegesis, with an ETRX2 module, acting as coordinator, and a wireless sensor node acting as RFD.

The coordinator was installed in a fixed position, at a height of 1,5 meters, and the sensor node was positioned, for every distance, in three locations and with two different heights.

Propagation Modelisation

Two models have been obtained: one for straight areas, and one for curved zones.

Straight Zone

The signal losses are due to:

- Free space losses, applied to the direct radio beam.

- Losses due to reflection on the roadway walls. This factor will be very variable depending on the characteristics of the wall materials (reinforced concrete, rock, etc.), and the presence of metallic elements, including support..
- Losses due to diffraction of the ray on the walls. This factor will be especially strong in cases where the transmitter and the receiver are in the sane side of the tunnel, and very close to the walls.
- Losses due to different obstacles in the tunnel: railway carriages, fans, etc. In general, any obstacle with a size of the same order as the signal wavelength (in this case, λ = 12,5 cm) would affect the signal propagation.

With these considerations, the propagation model was approximated by a function like this:

$$L_{db} = K_1 + K_2 \cdot Log\ Frec_{GHz} + K_3 \cdot Log\ d_m + K_4 \cdot Log\ Hr_m + K_5 \cdot d_m + K_6 \cdot Hr^{K_7}$$

Being:

L_{db}: Signal Loss

Hr: Receiver Height above the floor, in meters
d: Distance from Tx to Rx, in meters.

So the received signal by a node will be:

$$P_{R(dB)} = P_{T(dB)} + G_{T(dB)} + G_{R(dB)} - L_{db}$$

In addition to this, it was observed that the received signal was also dependent on the position of the receiver in the tunnel with respect to the transmitter (same side, opposite side). Therefore three additional coefficients were added to weight the position: K_8 for the same side; K_9 for the middle position; and K_{10} for the opposite side in the tunnel. By means of regression techniques the optimum solution is:

K1 =	**49,136**
K2 =	**0,000**
K3 =	**16,805**
K4 =	**-3,261**
K5 =	**0,000**

K6 =	**0,000**
K7 =	**0,000**
K8 =	**2,881**
K9 =	**-0,724**
K10 =	**0,842**

$$L_{db} = 49.136 + 16.805 \cdot Log\ d_m - 3.261 \cdot Log\ Hr_m + 2.881 \cdot R - 0.724 \cdot C + 0.842 \cdot L$$

Note that this formula is fitted to 2,4 GHz. The model has got the following characteristics:

STANDARD DEVIATION	**6,01**	**dB**
MEAN ERROR	**5,39**	**dB**

A simplification of the model was also calculated, in order to decrease the number of variables in the prediction, without loosing accuracy. Trying with a model only dependent on distance (like the free space model), the coefficients are the following:

K1 =	**49,140**
K2 =	**0**
K3 =	**16,710**
K4 =	**0**
K5 =	**0**

K6 =	**0**
K7 =	**0**
K8 =	**0**
K9 =	**0**
K10 =	**0**

$$\boxed{L_{db} = 49.14 + 16.71 \cdot Log\ d_m}$$

The simplified model has got a standard deviation of **6.17 dB** and a mean error of **5.47 dB**. This model is much simpler for later calculations performed by a microcontroller.

Curved Zone

For curved zones the same procedure has been followed, calculating directly the simplified model, having the following results.

$$\boxed{L_{db} = 49.14 + 28.83 \cdot Log\ d_m}$$

STANDARD DEVIATION	**5,43**	**dB**
MEAN ERROR	**5,67**	**dB**

The following plots show the results of the theoretical model (**Figure 3.3.4-23**):

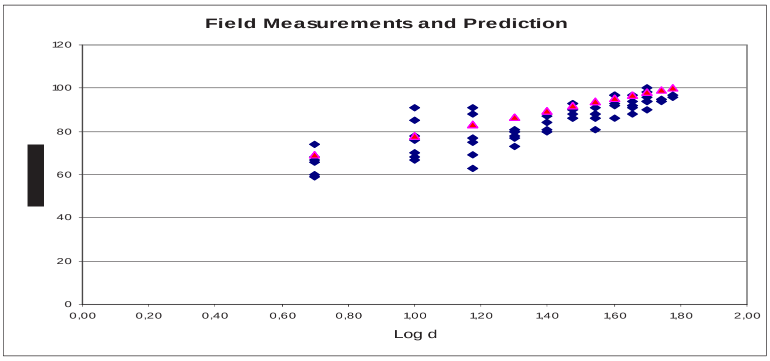


Figure 3.3.4-23: Prediction of signal loss. BLUE: Real data; PINK: Prediction

Propagation model conclusions

As expected, the signal propagation inside the tunnel is very sensitive to multipath. This fact is especially important when some of the devices involved in the communication (transmitter and / or receiver) are very close to the wall of the tunnel, and even more if the walls of the tunnel have got an irregular shape. Presence of obstacles, metallic or not, also affect to the propagation.

The propagation model objective of the current study must not take into account the presence of obstacles, due to they are usually mobile, and therefore no weighting factor can be applied.

Two models have been obtained for straight and curved zones:

$$\boxed{L_{db} = 49.14 + 16.71 \cdot Log\ d_m}$$ **STRAIGH ZONE**

$$\boxed{L_{db} = 49.14 + 28.83 \cdot Log\ d_m}$$ **CURVED ZONE**

According to the field measurements and the later analysis, the following network design recommendations have been extracted:

The signal loss prediction is better when the main component of the receiver signal is due to the direct ray, more than the reflected and diffracted ray. Therefore, in a real situation the direct ray must be searched for in most cases. Because the position of the sensor nodes is not predictable, two alternatives for installation are considered:

i) To install the network devices (Coordinator and Router) in the middle of the roadway, close to the ceiling.

ii) If the first alternative is not possible, a zigzag location should be considered, installing the network nodes on the sides of the tunnel, as high as possible, alternating the side from one device to the next (**Figure 3.3.4-24**). This way most of sensor nodes, if not all of them, will always have a network node in a direct ray. The picture below shows the proposed layout (a) and a possible association of sensor nodes to the network node depending of the location of the sensors (b).

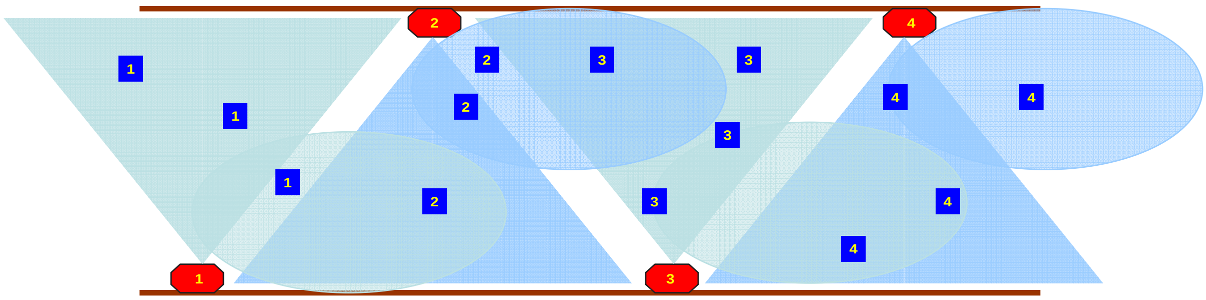


Figure 3.3.4-24: Sensor Nodes and Server Nodes

Following these recommendations will allow to increase the distance between consecutive network nodes (that was originally fixed to 50 – 100 m), because a more accurate distance prediction is achieved. This will cause an installation and equipments cost saving. A first target distance between nodes would be about 150 – 200 meters, or even more considering the nodes are equipped with high gain directional antennas. Trials based on the results obtained from the propagation model and further information about maximum link distances are reported on WP5 and Deliverable D5.3.

Location system based on WLAN

Principle trials with wireless LAN equipment were carried out in the training mine (TBW) and also in different underground mines. For these tests operationally used pocket PCs, access points and the new software were taken. PermIT.Pos is a software for calculating and displaying the position of pocket PCs with their IP-Address between two or more access points. The results of the trials are already reported in the current report in WP3, task 3.4 “RFID based navigation and tracking”. This new tracking application PermIT.Pos for location of Wireless LAN equipment is also suitable to be used for personnel location.

3.3.5 Operational trials programme in underground mines (Activities WP5)

3.3.5.1 Test-run, trials of Mines Rescue communications system in underground mines (Activities Task 5.1)

m-Comm Wireless Link Trials

The m-Comm wireless system as described in section 3.3.4.4 (Task 4.4) was subjected to extensive tests and underground trials in order to evaluate its performance and limitations against the project's key objectives. It was necessary to repeat these tests in different locations, with different equipment and with different operators in order to establish a mean and confidence in the results. With so many repeat tests only the salient and collated results are listed in this report. The reliability and availability of the whole m-Comm wireless system is considered paramount. Therefore the trials in underground mines and other similar locations were conducted to test all aspects of the wireless mines rescue communications system.

Wireless link results and performance

The limitations of propagating radio waves underground were described in Task 1.1. Based on this fundamental research, much of the subsequent work in development of the wireless mines rescue communications system under this project has centred on exploiting the latest low power wireless technologies. For practical reasons the Bluetooth, IEEE 802.15.1 standard, 2.4 - 2.4835 GHz technology proved the obvious choice for mines rescue communications. Had the Ultra Wide Band (UWB) wireless technology been more commercially advanced then it would have been adopted as the more secure option. Recognising that such wireless technologies are making rapid improvements and with new products or updated versions appearing nearly every six months the m-Comm wireless system was designed to interface with any low power wireless module. This design philosophy is primarily to ensure future proofing against obsolescence but will allow for the use of UWB at some date in the future.

Of necessity, the comparative performance of audio configured low powered wireless modules, i.e., set to minimum latency (data throughput delay), had to be made by determining the maximum working distance between two synchronised units. Most of the commercial wireless modules employed by RMT have no accessible signal level strength information. Line-of-sight (LOS) range is increasingly being cited in the manufacturers' literature as a comparative performance indicator. Furthermore, this can be formulated to show the determining parameters of a wireless module's performance. The dominant performance parameters are essentially; transmitter power, transmitter/receiver antenna gain and receiver sensitivity.

In working mines, this form of basic measurement is the only effective way of measuring, comparing and noting overall performance. The duality of the units under test allowed for one Bluetooth unit to remain in a location and typical orientation whilst the second unit was moved, rotated and placed against/behind various shielding or obstructions. The Free2Move Bluetooth module's internal on-broad antenna has a near omni-directional radiating and receiving pattern compared to a standard dipole antenna. This makes the unit orientation less critical.

The class II (+ 4 dBm) Bluetooth module selected, see Task 1.3, is specified to have a LOS range of 20 metres. There is a possibility of upgrading to a class I Bluetooth module increasing the LOS range to 100 - 150m but at the cost of increased power and hence reduced battery life. Whilst the nominal range of a class II Bluetooth is 20 to 30 m the tested open space (field) range or polar plot showed a much higher figure. The Free2Move, F2M03AC2, module consistently achieved a range of over 55 m with both units held at a height of 1.4 m above ground. Even with the antennae of the two modules in the worse possible orientation a range of 35 m was still consistently possible.

Better antennae designs are available, such as, Pinyon Technologies' resonant slot PCB based AirWire™ antenna which has a gain of 3-5 dBi. Its slightly larger two layer board design easily integrates to any 2.4GHz wireless module. The high gain is complemented by the antenna's unique band pass filtering properties that also rejects noise. The adoption of such antennae would double the LOS range without altering anything else.

Body shielding measurement

Having established an open space ‘range’ for the Free2Move modules it was necessary to quantify the loss of performance or range with the modules placed in different locations on or near the operator, as the wireless link has to function in realistic rescue conditions where the operator may be crawling through a narrow opening, or similar.

Early open space testing confirmed the degree of signal attenuation caused by the obscuration of an operator’s body. For example, when the wireless unit was held very close to the chest a cardioid shape polar plot with the maxima and minima of 55 to 65 m and 5 to 8 m respectively was produced. The minimum was produced with the body directly between the two wireless modules. It was also noted that, in the body shielding tests, the closer to the body the wireless unit (antenna) was placed the greater the loss of signal. With the wireless unit at a practical distance of about 6 cm away from the operator’s chest the body shielding signal losses were more acceptable, i.e., a minima of 15 to 16 m. Repeating the tests with the operator’s head between the two modules resulted in a minimum of 12 to 13 m and a maximum of 55 to 65 m. These results were obtained in a large open field setting, with light working clothes and an average body mass person.

Equally urgent for the ATEX submission, transmission range tests were made to evaluate the effect of a metallic antistatic case cover. Metal banding was considered the best solution to accommodate the antistatic ATEX requirements (in a hydrogen air mixture) for the case, reducing the exposed plastic surface to the approved maximum of 16cm sq. Carbon load plastic was a less favoured solution because of cost and questions of attenuation, particularly at 2.4 GHz. The metallic band has two strategically place holes of greater than quarter lambda dimensions (at 2.4GHz), see **Figure 3.3.5-1**. The design criteria for a parasitic slot-antenna were employed. Two practical design options were calculated, fabricated and evaluated; one with a round hole and one with a square hole. Both hole designs allowed the internal antennae to radiate as effectively as with just a plane plastic case with a free space range of 55 to 65m. Surprisingly, the antistatic metallic bands with the round hole improved the performance of the wireless units in the repeat body and head shielding tests, see table of results below.

	No metal band	Square hole	Round hole
Body shielding	15 – 16 m	13 m	16.7 m
Head shielding	12 – 13 m	9 m	13.3 m

Note: the higher the range/distance figure, the better the performance.

Figure 3.3.5-1: The prototype mobile wireless unit with its metallic antistatic band. Note, the strategically placed round hole of greater than $\lambda/4$ at 2.4 GHz

The most noteworthy observation from initial testing was the degree of signal loss with close hand shielding. Not surprisingly, pinching the on-board antenna with finger and thumb would stop all transmission. What was not fully appreciated was that a cupped hand over the antenna section of the wireless unit could have the same effect as that of body shielding. Investigation into the design and construction of a Nokia mobile phone revealed the same problem; cup a hand tightly over the top half and note the reduction in signal strength ‘bars’. The m-Comm wireless mobile unit has now the same ergonomic bias for the user to handle the mobile wireless unit by the lower half. And with the internal antenna placed in the centre of the top half there is less likelihood of hand shielding. The problem was not as acute in the handheld unit.

Structural effects on range

Initial tests indicated that the class 2 Bluetooth modules should maintain the specified minimum 10 m range in nearly all practical operational circumstances. Surface conducted tests around 90 degree stone or brick corners, metal structures and through brick and semi-open metal work consistently achieved a range of over 10 m.

It was later observed that surface, or free space, tests around corners and structures were consistently more signal 'lossy' than similar tests made in confined spaces. It is easy to lose sight of the complex behaviour of radio waves especially in enclosed areas. The reflected wave from internal walls etc., can make considerable contribution to the strength of a received signal. The summation of these reflected waves will however be algebraic, i.e., they can reduce the resulting signal as well increase it. Thus, all subsequent tests and range measurements were made in enclosed areas. As an illustration, the series of open space tests was repeated in a convenient corridor outside the m-Comm research laboratory, see **Figure 3.3.5-2**. The comparative results are tabulated below.

	Maximum distance measured with F2M module	
TEST	OPEN SPACE	CORRIDOR
Line-of-sight	55 to 65 m	48 m, limited by corridor length
Body Shielding	15 to 16 m	16 to 29 m
Head Shielding	12 to 13 m	14 to 18 m

Figure 3.3.5-2: Comparative confined space range tests of the Bluetooth wireless voice link at the Bretby laboratory

The variation in the above tabulated results accounts for the spread of readings with location, orientation and participating operator. The corridor in the Repton building at RMT's Bretby laboratory is built with double brick internal walls and reinforced concrete floors and ceiling.

Again, as an illustration of the differences between open and closed space propagation pattern, tests were made in and around a large steel container/structure, see **Figure 3.3.1-3.** The two deck structure is a navel fire training facility destined for The King Abdulaziz University, Facility for Marine Science, and built by Simulation Ltd., UK. With one wireless handheld unit at point 'A' the other mobile unit 'B' was able to operate in all internal compartments, see **Figure 3.3.1-3**, even with bulkhead doors closed. It was observed however that the bulkhead doors were not of a watertight seal design, and had physical gaps of a few centimetres around the doors. The plan view of the steel structure, **Figure 3.3.5-3**, shows the limit (shaded/hashed area) of the wireless reception area.

Co-channel interference tests

In the envisaged working arrangement of the wireless m-Comm system there can be multiple hubs and mobile units working in the same area. Checks were made on two Bluetooth paired units in the same areas. No interference could be detected, nor was the range performance compromised. After reference to the work on co-channel interference in Task 3.6 different units were placed together to check for extreme front end amplifier overload problem. Again no adverse effects could be detected. A variety of FM wireless low power audio modules (mostly used in the initial RAINOW project propagation evaluations) were also found not to cause interference with the Bluetooth units.

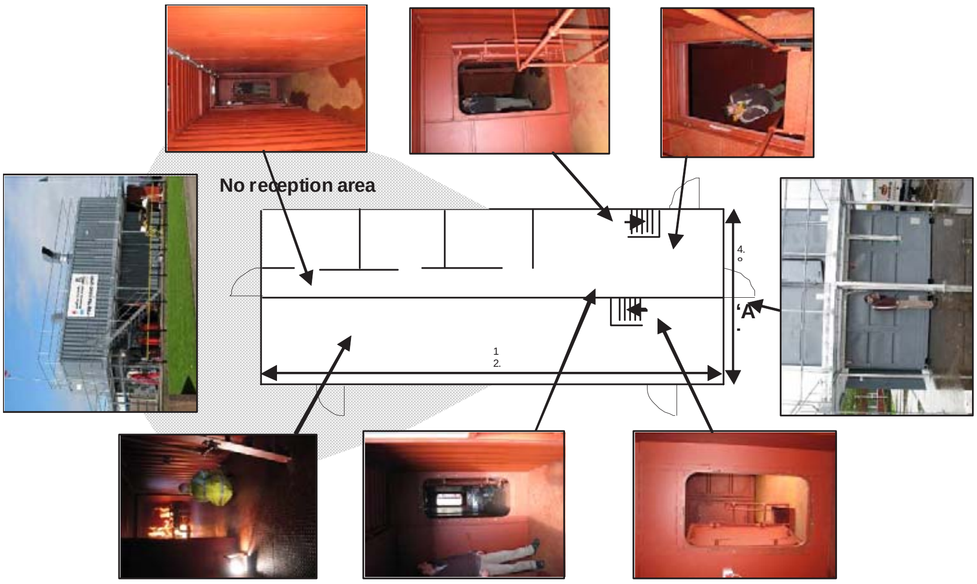


Figure 3.3.5-3 Performance testing of the pre-production wireless units in and around a two deck navel fire training facility. Contrast the no signal (hashed) area on the outside with good reception in all internal compartments from point 'A'

The effects of mutual interference between the main types of low power wireless band 2.4 GHz devices were demonstrated and tabulated in Task 3.6. The associated report logs the degree to which ZigBee, Bluetooth and 802.11x WiFi will cause mutual interference in a tunnel environment. In this report the system performances were measured from the bit error rate or conversely the data throughput. However, in RMT's tests, with Bluetooth wireless devices set for voice transmission, there was no similar data error reading available. The lower data throughput requirement, or latency mode, of voice mode Bluetooth system does enables a greater degree of tolerance of co-channel interference.

Underground tests

The main underground tests were conducted at the Bath Stone Mine in Wiltshire.

Figure 3.3.5-4: Overview of the wireless rescue communications trials at Bath Stone Mine, Wiltshire, UK

The test site had to be gas free as the prototype units were not fully ATEX approved at the time. The mine plan, see **Figure 3.3.5-4** shows the location of 29's working area where most of the testing took place. The Bath Stone mining operation is bord and pillar and in parts requires roof supports in the form of rock bolts and steel mesh. Roadway openings vary between 3m by 3m and 3m by 4m. At the time of the tests most of the mine was wet but well ventilated.

The m-Comm wireless test equipment comprised the standard prototype units fitted with the F2M03AC2 and a separate prototyping kit with the latest version of the F2M03ALA Bluetooth modules. The newer version has improved receiver sensitivity (-86 dBm) which should provide a better overall working range without requiring more power. The F2M03AC2 wireless units were built into the ATEX designed pre-production m-Comm handset and mobile unit whilst the F2M03ALA modules were tested on a self powered development interface board. All units were protected from the damp and humid conditions; a lesson learnt after experiencing problems with wet conditions at a full m-Comm system test and demonstration at the Holman Test Mine, Camborne School of mines, Cornwall, UK.

The results from a typical 90 degree roadway corner, on the way to 29's face, with the stationary (hub) unit 3 m from the corner, see roadway and roof conditions in **Figure 3.3.1-4**, were as follows:

- 10 to 12m around the blind corner from both mobile units (13 to 15 m in total) and,
- 21 and 38m line-of-sight with F2M03AC2 and F2M03ALA respectively.

These measurements are the lowest average readings of several tests. As can be seen from the photographs, the units were operated by a fully equipped contingent of the mine's rescue team undergoing routine training. Their response to the wireless m-Comm is reported below.

Line-of-sight measurements were made at several locations and each one gave a slightly different maximum reading. The LOS measurements reported above gave the lowest while the best gave distances of 41 m for the F2M03AC2 module and 63m for the F2M03ALA module. **Figure 3.3.5-.4**, shows the dryer and slightly wider test area which gave the better LOS distances.

In a 'straight' roadway with side tunnels, an obscuring vehicle had only a modest reducing effect on range of 4 to 7 m depending on location from the side wall of the receiver unit. There were no large null signal areas in the shadow of the vehicle but the vehicle used in these tests was only 1.2 m high, see **Figure 3.3.5-4**.

At 29's working area it was also possible to test the units from within windowless galvanized steel containers, one used as a mess room and the other as a 'safe haven' in the event of an emergency, see **Figure 3.3.5-4**. Tests were carried out with the less sensitive F2M03AC2 units only. With the steel door closed (against rubber seals) a good signal was obtained from inside and up to 10 m in one direction of the mess room. In the other direction, a signal was also received up to 4 m around the corner in the road way and out of sight of the mess room door. As a final test, one unit was operated from inside the mess room to the other unit in the 'safe haven' with just occasional break-up as the unit was moved around within the room. Both container doors were closed during the tests. On close inspection the steel containers were not totally sealed, as there were small gaps around the edges of the corrugated steel cladding. However, the 'safe haven' container was said to be safe from smoke in the event of an underground fire.

Equipment performance and certification

In general, the equipment performed flawlessly. The only negative comment noted was the lack of sound level when operated next to an extraction fan. The plug-in earpiece helped but with such a high ambient noise level it too was inadequate. This lack of sound volume results from the ATEX restriction on speakers or earpiece maximum drive current.

The mobile unit operating with the F2M03AC2 recorded two current levels, 49 mA when searching and 32 mA when synchronised, i.e., normal mode. At 32 mA its Ni MH battery would last for about 26 hours. The operational extra current drain measured during tests with the modified m-Comm handheld unit (hub) were, 1 mA to power the FX465 and PIC processor and 32 mA to power the synchronised F2M03AC2. Thus the handheld hub had a current drain of approximately 56 mA in receive mode, Rx, and 99 mA in transmit mode, Tx. This translates to 15 hours continual operation in receiving mode or, theoretically, 8 hours in continual transmit mode. At 100 mA drain, this 8 hour figure would not be achievable since the battery chemistry would need some recovery time. Both m-Comm handheld and mobile units were deemed to have adequate energy margins to cover a 12 hour typical operational period, with the standard 80% receive and 20% transmit mode periods.

The current Ni MH battery technology should provide adequate margins for use in zero temperatures and through the normal life of the battery pack. Ni MH has 800 to 1000 charge discharge cycles, better than most other cell types and, from experience, is most resilient to abuse. The cell protection requirement for Ni MH chemistry is much less onerous than, for example, a lithium ion rechargeable cell.

An application for ATEX certification of the wireless m-Comm was submitted to SIRA Test & Certification Ltd, on completion of the design, fabrication and testing of the production prototype. In fact, two separate applications were made, one for methane/air mix and a multiple unit application for hydrogen/air mix, as follows;

- Base unit, for use in methane/air mix.
- Handheld unit (wireless hub) for use in hydrogen/air mix.
- Wire dispenser reel (wireless hub) for use in hydrogen/air mix.
- Mobile unit, for use in hydrogen/air mix.

As was stated earlier, the wireless module is to be certified as an unspecified module subject to the usual limits of total L, C and no voltage generating components etc. The conflict between the need for antistatic case material for the mobile unit and transparency to radio waves was discussed above as was hand shielding.

Operational performance and observations

As with the equipment performance, no adverse comments were voiced or operational difficulties observed during the various trials underground. The rescue team members were new to the equipment and received very little training other than how to place the mobile unit in front of the breathing apparatus' face mask diaphragm and operate the press-to-talk button.

As a result of earlier operational trials the mobile unit was made to function in the same way as the handheld unit, i.e., with press-to-talk (PTT) operation. This proved intuitive to the operatives in the Bath Stone mine and in other trials. The same principle was applied to the handheld unit. For any out going communications, whether to the base or the mobile, both receive the message. In this way, local inter-team communication (between the handheld unit and mobile) can always be monitored by the base unit.

After many laboratory tests with different microphone and earpiece arrangements the units used in the underground trials were a) the compact mobile unit with its inclusive microphone, speaker and PTT button and, b) the same unit but with external plug-in microphone and/or earpiece. This optional plug-in arrangement has the potential to satisfy most users' requirement and, from a reliability point of view, retains the facility to revert to a robust basic unit.

Out of range problem

The loss of synchronization when the units went out of range did unnerve the operators at first but they soon became aware of the range limitation and the need to re-synchronise. To re-synchronise the operators had to be trained to move back towards the handheld hub/unit and wait what (to them) seemed a long time. It actually takes 3 to 4 seconds in a good signal strength area to synchronise the wireless units.

The ability to range well over the stated 10 m lulled the operators into a false sense of limitless wireless coverage. In action, losing contact at a vital moment could, at best, be annoying and at worse cause an unsafe situation. A warning of the approaching limit of reception would be ideal but is technically very difficult with Bluetooth technology. Tests in various locations underground demonstrated that, on the limit of reception, sound quality did start to degrade and give a degree of warning. Rescue team members agreed that they could be trained to recognise the signs of signal break-up before loss of synchronization. The delay between loss of signal to loss of synchronisation was increased in an attempt to alleviate this abrupt loss of synchronisation. The extra delay was perceived to be beneficial.

With training, an operator should be better able to keep wireless units within working (and synchronised) range.

Bluetooth Intercom Trials

In order to perform the functional trials of the advanced roadway amplifier with wireless communication based on Bluetooth technology, the tests of the equipment were performed in a real situation. The scenario selected was the development face in one of the tunnels of Laciana Labor School (property of “Fundación Santa Bárbara”), located in León (Spain).

The working area around the face contained all the machinery and personnel responsible for face development, therefore a common roadway amplifier for mining applications is usually installed into this area. This kind of system allows to the miners to establish voice communication with the surface or other locations.

However, the high noise level caused by the development process usually makes it impossible to hear the sound provided by the roadway amplifier speakers. Most of the time, this kind of device incorporates high visibility lights to alert the personnel of incoming communications, although it does not avoid workers having to disrupt their work to answer it.

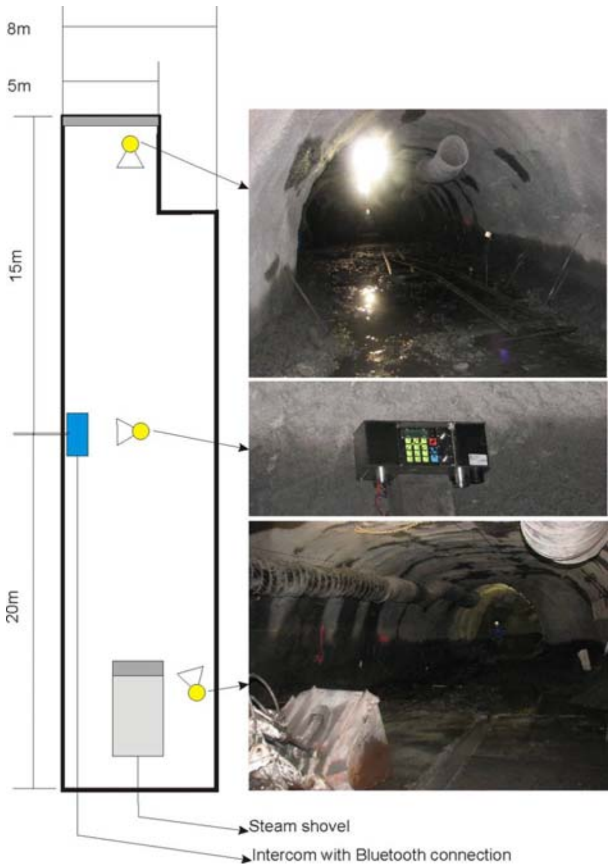


Figure 3.3.5-5: Scenario layout and intercom location during trials

Employing wireless devices capable of connecting the workers directly to the trunk voice line of the installation could solve the problems mentioned above, as well as introducing other benefits, specifically in regard to safety. Therefore, a prototype of the roadway amplifier was installed into the development face area mainly to assess the wireless coverage and the integration with the existing voice system based on RELIA (monitoring and control system for mining applications developed by AITEMIN).

Figure 3.3.5-5 shows a schematic layout of the development area including some pictures displaying the scenario and the location of the amplifier during the trials.

During the trials a wireless link between the roadway amplifier and a portable device was established. The intercom uses a Class 1, version 2.0 Bluetooth module (BlueRadios manufacturer) as the wireless transceiver. It theoretically allows a link up to a range of 100 meters LOS (Line of Sight) propagation. However, a standard cell phone was used as a portable device. The use of a commercial device instead of another module mounted into the intercom makes it easier to develop the device firmware according to standard connection procedures and protocols. On the other hand, like most of these kinds of commercial devices available on the market, the cell phone incorporates a Class 2 Bluetooth transceiver, so a maximum link distance of 10 meters is expected.

The use of Bluetooth 2.0 technology allows multi-point communication. It means that various headsets or portable devices can be simultaneously connected to the intercom device (**Figure 3.3.5-6**).

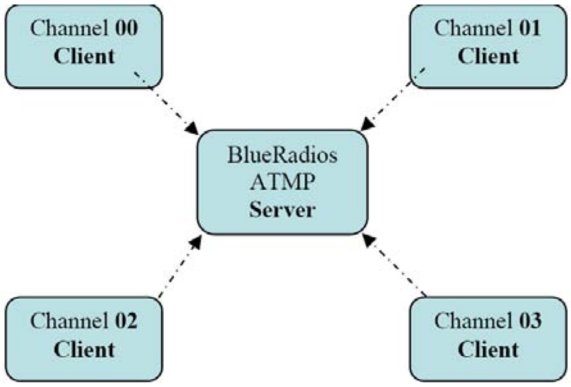


Figure 3.3.5-6: Example of multi-point Bluetooth connection.

The roadway amplifier integrates the Bluetooth module with the keyboard on the front. The metallic contacts in one of the keys (previously used for speaking through a wired earphone) have been removed, in order to provide a gap for the radio signal from/to the aerial located just behind it. However, there is only a gap of 20x20mm in the steel cover (next to the aerial) for the signal to propagate through. This is less than both the recommendations specified by the manufacturer and the wavelength of the Bluetooth signal. Consequently, in order to know the signal losses caused by the device enclosure, the link distance test was repeated in three different situations; i) the intercom completely assembled (casing and keyboard), ii) with only the keyboard (casing removed) and iii) with the keyboard and the casing removed (bare module).

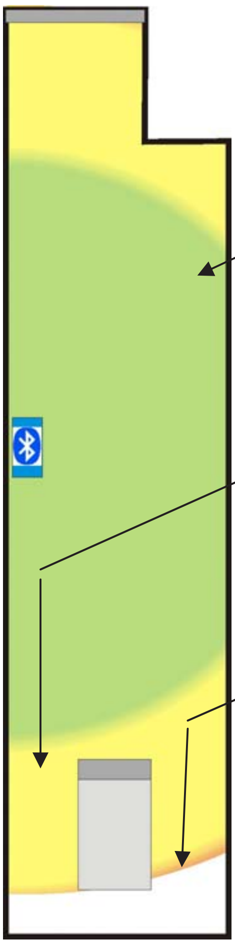
The results presented in the **Figure 3.3.5-7** show the zone with an acceptable voice quality. This area can be extended by around 15% but the communication could get unintelligible (depending on the obstacles between the intercom and the portable device). The use of Class 1 modules also in the portable devices should extend the area of Bluetooth coverage up to 60 meters (minimum radio).

In order to have a better knowledge of the radiation pattern of the Bluetooth module through the steel cover of the intercom, the equipment was also located on the shovel with the front facing to the end of the tunnel (**Figure 3.3.5-8**). This position permits the maximum link distance to be determined in the area just in front of the device. The following pictures show the device on the shovel and the connection process with the portable device.

A link distance of 10 meters (including keyboard and steel cover) was obtained just in front of the roadway amplifier, confirming that the radiation pattern of the signal can be considered as a semi-circle, at least along the horizontal plane (parallel to the tunnel floor).

Although practically all of the working area in the selected scenario can be covered with the installation of only one roadway amplifier, depending on the application (surface, layout, etc), a larger coverage area may be needed. A possible solution could be to replace the internal aerial by an external one placed on the device. Nevertheless, some mechanical aspects especially related with the robustness of the equipment must be borne in mind if this solution is implemented.

From the point of view of safety, the integration of wireless connectivity into this kind of roadway amplifier allows personnel to be continuously in contact with the trunk voice line even in the case of an emergency. The intercom is designed to transmit and receive voice through both a digital data bus based on RS485 (normal situation) and a analogue voice backup line totally independent of the digital signal stream (in case of emergency) that can work even when a general power supply failure occurs. In that situation the intercom (powered by its own internal battery) converts the analogue signal coming from the emergency line into digital frames ready to be transmitted to the wireless devices situated into the coverage area.



The above pictures show the device during the three test series (from top to bottom; i, ii, iii) and the left figure illustrates the results obtained in each case.

i) During the test performed with the device completely assembled, a coverage radius of 10 meters was achieved. [Green Area].

ii) Once the casing was removed, the coverage area was extended up to 15 meters. [Yellow Area]

iii) A slightly improvement was observed by removing the keyboard as well. The radius of the coverage area was extended only 1or 2 meters. [Red Area].

Figure 3.3.5-7: Test series

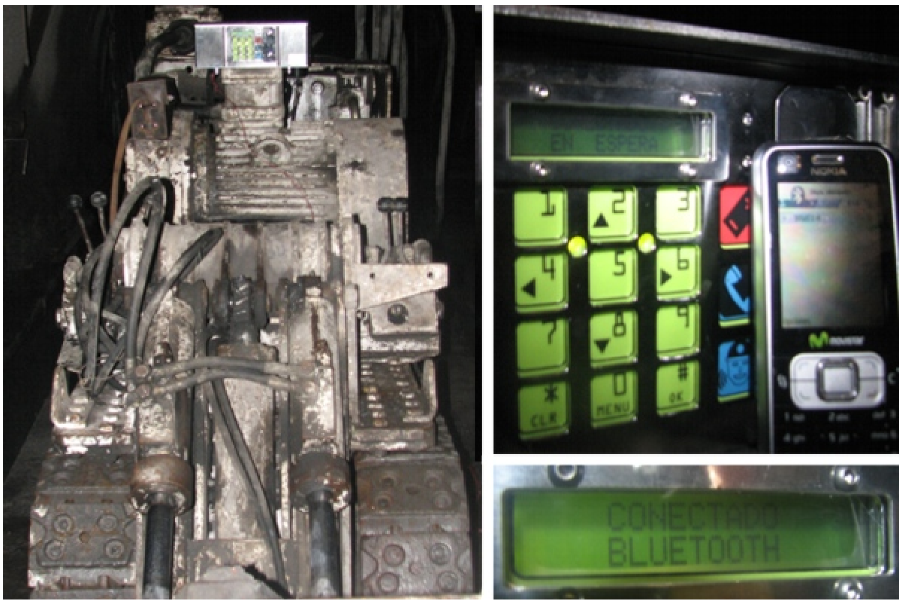


Figure 3.3.5-8: Intercom on the shovel (left). Intercom and cell phone during the link establishment process (top-right). Intercom displaying a message confirming a successful connection with the portable device (bottom-right).

The use of Bluetooth technology also allows the intercom to know which devices are located within its coverage area. These devices can be identified by their unique MAC and the intercom can also transmit this information through the data bus to the central station or SCADA system. Given that the intercoms are placed in known locations, this information can be used to determine which personnel are working in each area. This could be very useful during a rescue or an evacuation. This method could work together with the tracking and guidance system developed under T4.6 and tested in T5.3.

3.3.5.2 Installation and trials of Smart Sensor Networks (Activities Task 5.2)

During this task the wireless mesh smart sensor system that was developed under WP3 was trialled. Tests were carried out using EmberZNet / EmberNet wireless mesh networking technology, further tests were carried out comparing ZigBee mesh system from different vendors, and finally, the smart sensor system developed under WP3 was evaluated and trialled.

Underground Mine Mesh Network Performance

Initial tests were carried out at CSM (Camborne School of Mines) Test Mine, in the UK, using EmberZNet / EmberNet wireless mesh networking technology with 5dBi omni-directional gain antennas in order to investigate the network performance. Previous tests had been carried out at the same location using the EmberNet devices with standard 2dBi isotropic antennas, during a previous ECSC project - 7220-PR/133. The results obtained during research carried out in WP1 of the RAINOW project, concluded that a waveguide effect occurs at high frequencies (e.g. 2.4GHz), and directional antennas offer better coupling to the waveguide propagation modes, and hence improved transmission. The purpose of these tests was to examine the overall transmission and networking performance of the EmberNet system using the higher gain antennas. Many of the applications under RAINOW have been developed using EmberNet and EmberZNet wireless mesh technology; therefore these tests provided useful information for optimising such technology.

The mine-wide mesh network was established, as shown in **Figure 3.3.5-9**, below. Using the 5dBi omni-directional antennas, there was an increased number of non line-of-sight signals present further verifying the observation that a wave guiding effect was present. The effect of a break in communication between two nodes was simulated between 0721 and 070d, where the network demonstrated high resilience in terms of re-routing data through multiple redundant pathways. A range of further tests were carried out using this network along with other EmberZNet related technology from Maxstream (XBee) and Telegesis (ETRX1 and ETRX2).

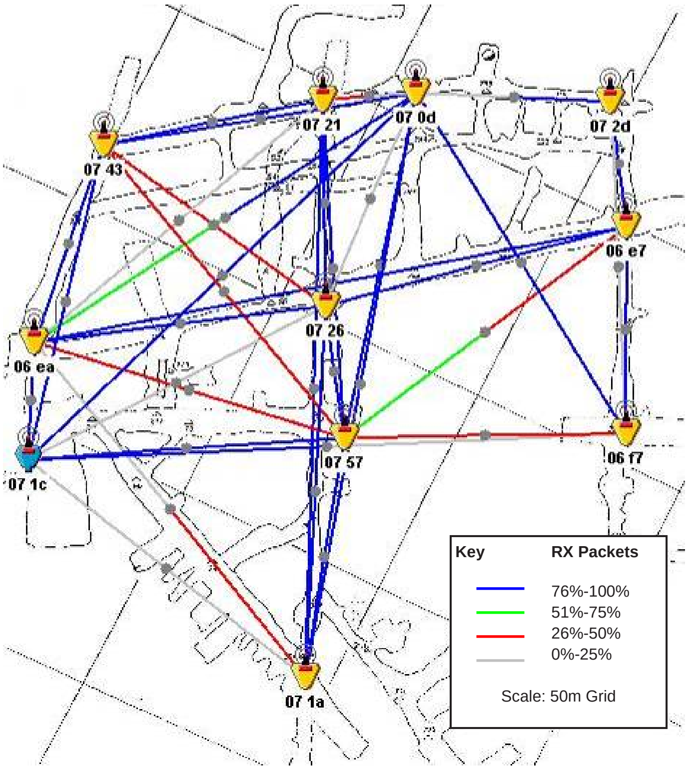


Figure 3.3.5-9: Mine-Wide Mesh Network – 2.4GHz, 5dBi Omni-directional Antennas

Smart Sensor System Trials

The wireless mesh smart sensor system developed under WP3, as discussed in Section 3.3.3.1, has been evaluated and tested out during this task. The system was developed using EmberZNet technology and ETRX2 radio modules incorporating the Ember EM250 microchips, as selected during the earlier research under WP1. The system relies on a sensor-sink approach where the sink device acts both as a data collection point for the ZigBee network and a gateway, which interfaces to either a larger backbone network (e.g. TCP/IP) or to a local PC. The wireless smart sensors themselves are designed to interface to various types of transducers for applications such as underground/mine environmental monitoring and control. The trials were conducted with the wireless mesh smart sensor network to determine the performance in terms of sensor accuracy, using different types of sensors and gathering real-time data remotely.

In order to fully test the wireless mesh smart sensor system's functionality a range of sensors were interfaced to the smart sensor devices. **Figure 3.3.5-10** below, shows a photo of both a PRT (platinum resistance thermometer) sensor and a barometric pressure sensor that were trialled.

Figure 3.3.5-10: Temperature Sensor (PRT) and Barometric Pressure

The web server display, displays real-time data from the smart sensor network. The data is collected on a PC using a program written in Visual Basic to gather the incoming 'sink' node data, which is interfaced either through a local serial COM port or remotely on an Ethernet TCP/IP link. This data is then stored on a MySQL database. The web server runs a PHP program to gather information stored on the database and display real-time graphical data, as shown. The entire web server application will automatically recognise new sensors being added to the network and the graphs will automatically be displayed.

The wireless mesh smart sensor system that was developed under WP3 has been trialled during this task. Initial trials were carried out using EmberZNet/EmberNet technology in order to examine the network performance, particularly in regard to improving the transmission using omni-directional gain antennas. The smart sensor system was developed using EmberZNet / ZigBee technology. The effect of a break in communication occurring was simulated (e.g. a roof rock fall occurring), where the packets are sent across other multiple-routes and the network sends data via the lowest cost route. The 'cost' is established by the network stack through comparing signal strength, link quality and number of hops. Also, with the availability of multiple vendors of ZigBee and EmberZNet technology, trials were conducted comparing a selection of technology options available using different antenna configurations. Finally, the actual smart sensor network system, which was developed under WP3, was also tested out, particularly examining issues of actual sensor interfaces (PRT and barometric pressure), determining measurement accuracy of the EM250 chip, and enhancing the application functionality such as providing real-time data display and scalability.

Smart wireless sensors and active transponders (active RFID).

RAG tested a) smart wireless sensors and b) active transponders (active RFID). These trials were carried out in the training mine of RAG (RAG Trainingsbergwerk "TBW").

The training mine (TBW) is a replica coal mine. This facility is built on the surface into a waste heap (tailings) of the former Recklinghausen coal mine. The training mine is completely fitted with German colliery equipment. The facility is lined with steel circular roof supports, has various machinery, pipes and cable work and the inventory is typical for a European coal mine. There are also two replica coal faces; a shearer longwall face and a plough longwall face. With different production mechanisms, with roadway drivages and with a shaft the mining underground is realistically represented here. The infrastructure of a mine is normally over 1,000 meter deep under the surface and distributed over many square kilometers. In this training facility are the most important machines and equipment of the production, transport, communication and control units concentrated in a manageable (visible) area. TBW is used by RAG for training staff in health and safety issues, maintenance practice training, and testing and researching with equipment which does not yet have the necessary underground ATEX certification. The main advantage of the RAG training mine facility is that it provides a safe working environment where training / research can be conducted without disrupting any real mining operations. The facility provided an easily accessible and non-regulated typical coal mine environment to conduct the wireless sensor trials and the active transponder trials (trials with active RFID). Because during the development and testing phase the wireless sensors, the base station and the necessary measurement equipment did not yet have an ATEX certification, the underground trials were not possible in a real mine of RAG. The longest distance (straight line) in the area of the training mine (TBW) is about 100 meters (see **Figure 3.3.5-11**).

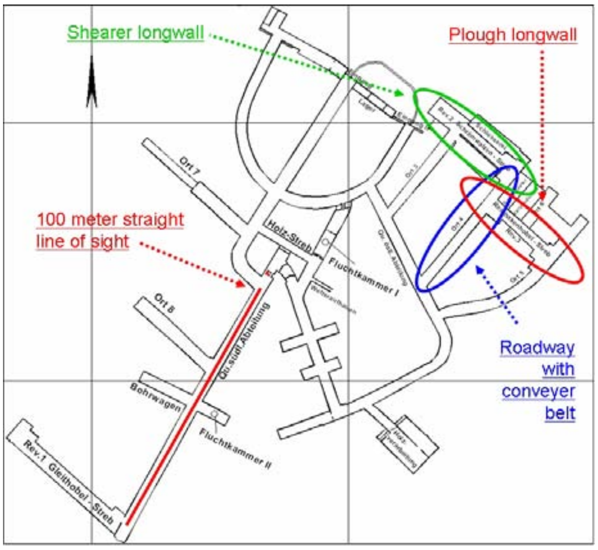


Figure 3.3.5-11: Test areas in the training mine

a) Smart wireless sensor tests

The wireless sensors employ chirp modulation scheme for the transmission, which was found to require low power and be characterized by high resilience to interference. The wireless sensors were operated in the principle that a beacon signal was sent periodically (to confirm sensor operation) and the measurement values were sent only when a measurand change occurred. Further technical details are reported in work package 2 (WP02).

In the year 2008 the new smart wireless sensors (final generation prototype), with a power of 100mW, were available for trials in the training mine. RAG obtained also a new I/O Unit and a new Processing Unit with improved software versions (**Figure 3.3.5-12**). The test system consisted of the following components:

- 1 I/O Unit
- 1 Processing Unit
- 1 Measuring sensor with seven
- segment display
- 2 Digital input sensors
- 2 Access sensors
- 2 Temperature sensors
- 2 Humidity sensors

Three different tests were carried out with the new wireless sensor equipment in the training mine:

- with the standard antenna in a 100m roadway, in the “Crossway, Southern Section” (Querschlag südliche Abteilung)

- with the standard antenna in a roadway with conveyer belt
- along a LeakyLineAntenna (200 meter)

The first test was carried out in the 100m roadway “Crossway, Southern Section” (Querschlag südliche Abteilung, see **Figure 3.3.5-11**) with the standard antenna. At first the wireless sensors were positioned along the roadway in a distance of 10 – 15 meter. The result for the standard antenna was a maximum signal quality over the complete distance of the 100m. Then all wireless sensors were positioned at the end of 100m roadway with the same result (see **Figure 3.3.5-13**).

Figure 3.3.5-12: Test system with I/O Unit, Processing Unit, sensors and measuring module (with seven-segment display)

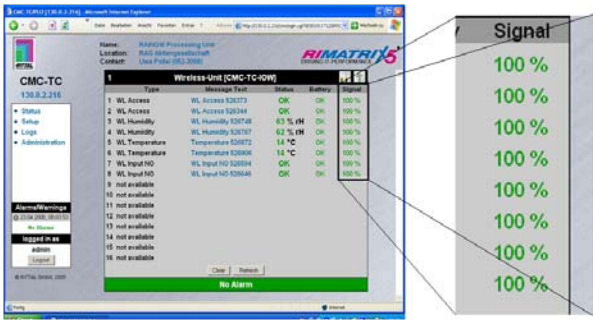


Figure 3.3.5-13: Display of the results

The second test was carried with the 100mW wireless sensors and with a LeakyLineAntenna. This LeakyLineAntenna was a prototype with a length of 200m and was an achievement from work on the R&D project "IAMTECH" (RFCR-CT-2004-00001). A LeakyLineAntenna is a co-ax cable, which has openings in the outer sheath at predefined points (the outer sheath of the co-ax cable is deliberately interrupted at defined points – with other words: the cable is “leaky”). A LeakyLineAntenna is ideal for utilization in regions of branchings, within curves, around corners and also useful before, between and after ventilation doors and in the longwall system of underground mining operations. The wireless sensors were positioned along the 200m LeakyLineAntenna, which was arranged along a way with many curves, corners and junctions (**Figure 3.3.5-14**). The result of this test was a maximum signal quality over the distance of 200m.

Figure 3.3.5-14: The LeakyLineAntenna (blue)

After this test a third test was carried out in a roadway with a conveyer belt (see **Figure 3.3.5-19**). For this test the wireless sensors were positioned along the conveyer belt and along the loader. The result was a maximum signal quality over the complete distance (Signal = 100% for each sensor).

Figure 3.3.5-15: Positions of the wireless sensors along the conveyer belt and along the loader (I)

During these trials the measurement results were also displayed on a computer at the headquarters of the RAG in Herne. The notebook had an Ethernet connection to a switch in the training mine. The training mine in Recklinghausen has a 20Mbps beam radio connection (point to point radio system) with the headquarters in Herne.

The lastly tested wireless sensors with 100mW power worked very successfully over a distance of 100m with the standard antenna and along the LeakyLineAntenna over a distance of 200m.

b) Active RFID transponder tests

Another important activity of RAG was carrying out different tests with active transponders, the transmitting / receiving stations and their necessary loop antennas (tests with active RFID). In the first half-year 2008 the improved new transponders (**Figure 3.3.5-16**) and the improved new transmitting / receiving stations with fibre-optic interface were tested successfully in the training mine. Further technical details are reported in work package 2 (WP02).

Figure 3.3.5-16: First prototype active transponders (above) and second generation (below)

The tests were carried out in an intersection area. The transmitting/receiving stations and the necessary loop antennas (9kHz magnetic field antennas) were installed within the range in front of a curve and behind a curve. For the loop antenna is now only a simple wire sufficient. A highly flexible wire (LiFY) with a cross section of 0,50mm² was used. These loop antennas completely covered the entire area of the roadway cross section (**Figures 3.3.5-17 to -22**).

Figure 3.3.5-17: Open case of the read/write unit with fibre optic interface and E2000 connectors

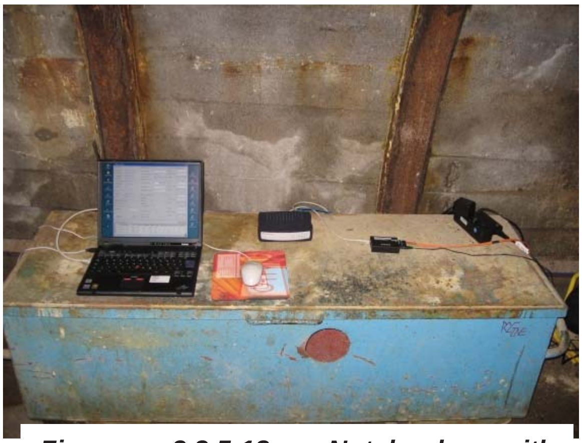


Figure 3.3.5-18: Notebook with visualisation software, switch and media converter during the tests

Figure 3.3.5-19: One of the two read / write unit during the tests (red wire = 9 kHz loop antenna, orange = fibre optic cable)

Figure 3.3.5-20: The loop antenna (red wire) during the tests

At these tests the 5 active transponders were positioned in the cage of a mining bicycle. Both stations were passed several times by the mining bicycle, all transponders were reliably detected (recognized surely) by both transmitting/receiving stations.

Figure 3.3.5-21: The mining bicycle in the area of the first read / write unit during the tests

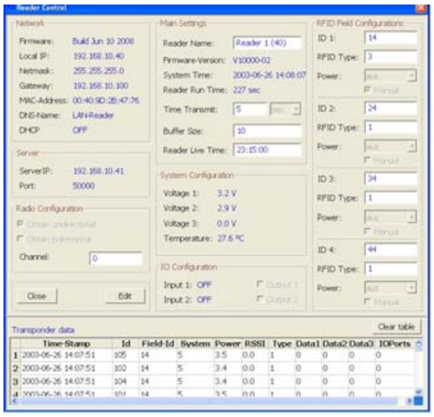


Figure 3.3.5-22: Visualisation of the results (Sample screenshot)

Rock Stress Wireless Sensor Network

In parallel to the tests described above, DMT carried out trials with rock stress equipment based on Nanotron’s Chirp-Transceivers. For these tests the hardware shown in **Figure 3.3.5-23** was used, where some developmed equipment described in tasks 2.3 and 3.3 tasks can be recognised.

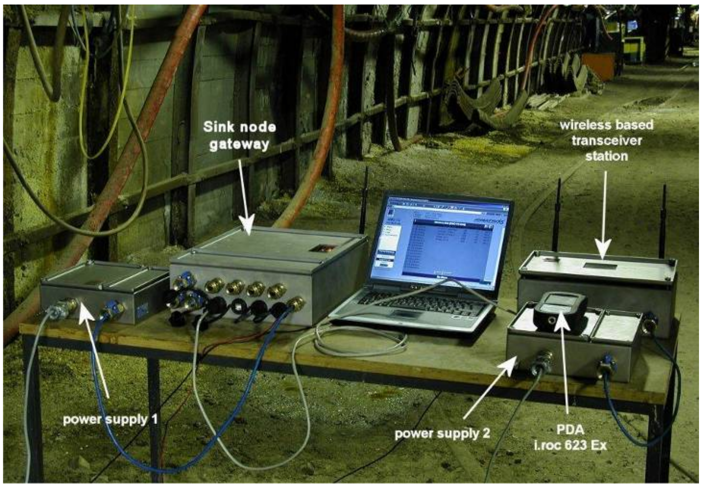


Figure 3.3.5-23: Rock stress test equipment based on WSN

Figure 3.3.5-24: Rock stress Chirp-sensor

On the left the “Sink node gateway” (see Task 2.3) constitutes both the connection to the ETHERNET-backbone via optical fibre and the interfacing to the “wireless based transceiver station” (see Task 3.3) via copper-ETHERNET. This copper interface with standard RJ45 plugs is already certified for mining applications.

For the tests the access point of the “sink node gateway” was used to connect both the notebook and the pocket PC “ECOM i.roc 623” via wireless LAN (WLAN) to the Wireless Sensor Network (WSN). As an alternative to the evaluation desktop-software, the server / client software (developed under Task 3.5) for PDA-access could be used as a replacement and tested this way.

The chirp sensors (implemented together with an analogue interface for the strain gauge inputs and housed within a mining resilient case - see **Figure 3.3.5-24**) were modified and connected to an external antenna with a gain of 4dB. To supply two Wireless Sensor Networks (WSNs) with appropriate gain, the “wireless base station” was equipped with two antennas of 7dB gain. Both can maintain radio-connectivity to 16 Chirps, so that up to 32 sensors could be connected to one of these base stations. During the tests, five “rock stress” sensors were employed on the first WSN and six standard ones for temperature, humidity and access on the second one.

Like the previous tests the 100m roadway in the southern section of the RAG training mine (TBW) was considered a suitable location and the five rock-stress sensors were positioned every 20 metres along this line. After the transmission-range tests, interest was also focussed on signal quality and precision data transfer in particular. For that a 500 bar pressure transmitter (see **Figure 3.3.5-25**) as well as two precision strain gauge simulator-bridges (**Figure 3.3.5-26**) were connected to the sensors, with their input signals fixed to definite values. The resultant measurement values were checked by the evaluation software on the notebook and by the new server/client software on the Pocket-PC (PDA).

In spite of some minor anomalies during the tests, excellent results were observed for both the transmission- range as well the accuracy of the data.

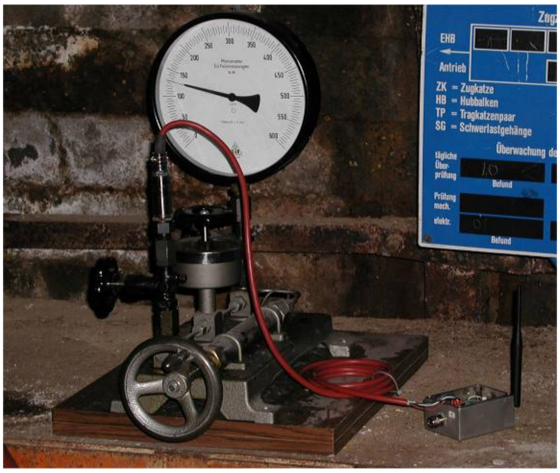


Figure 3.3.5-25: 500bar pressure transmitter

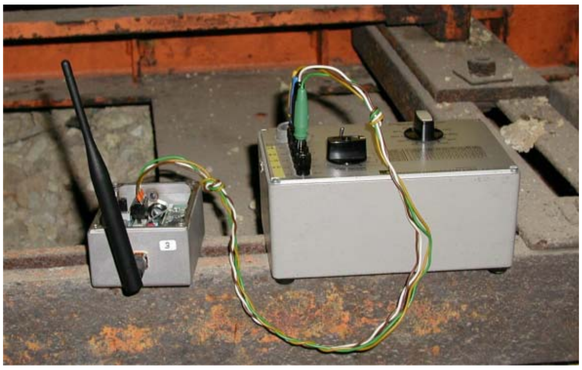


Figure 3.3.5-26: Bridge-simulator with Chirp-sensor

The occasional errors were observed sometimes as temporary zero-values and sometimes as temporary incorrect values. During the tests in TBW it was not possible to examine and solve this problem, but after rerunning these tests in laboratory, the cause was found in the evaluation software. Here the measurement polling was faulty, so that the synchronisation between the value-buffer within the base-station and the pick-up sequence of the evaluation software had to be retuned. After this modification all measurement transmission processes ran properly.

Transmission-range: Compared with the standard Chirp-Sensors (where the standard antenna is a simple semiconductor one), the transmission range could be enhanced by around 10% to 20% by using the external 4dB sensor-antenna (**Figure 3.3.5-24**). Also upgrading the base-station antenna from standard 4dBs to a higher gain 7dB or to even 12dBs, as done by RAG, could widen the transmission range by up to 10%. With the equipment shown in **Figure 3.3.5-23** it was then possible to register sensors, which were positioned 10 to 20 meters in a right-angled branching coal face at the end of the 100m-roadway.

Data-accuracy: The precision of the strain gauge circuit depends on a lot of different factors. The essential ones are the amplifier itself, the resolution of the A/D-converter and high precision tuning of the circuit. A low-noise rail to rail amplifier (OPA333) with very low power consumption and high linearity is responsible for the exact strain gauge measurement. And in combination with a 10 bit-resolution A/D-converter an overall accuracy of 0.125% can be achieved. After the high accuracy amplifier, the tuning of the circuit with regard to its linearity is very important. This was carried out with support of a high-precision Hottinger bridge simulator (as shown in **Figure 3.3.5-26**). All theoretical calculated values were confirmed by these tests.

Figure 3.3.5-27 shows screenshots of the PDA server/client software which is able to represent all measuring functions from the evaluation desktop software on the small screen of the Pocket-PC. The screen presentation and functionality of the software were proven.

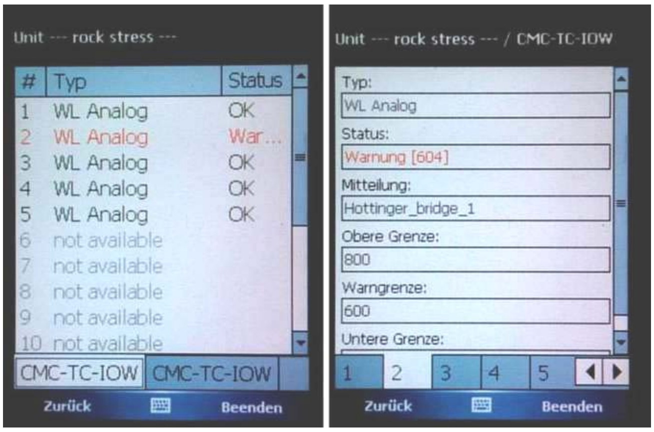


Figure 3.3.5-27: Pocket PC Display

The smart sensor network trials were done in the Laciana training coal mine located near to Villablino, León (Spain) with the collaboration of Fundación Santa Barbara, integrating the new technology with both the sensor elements installed along the roadways and the main monitoring and control system of the mine operations (RELIA 2000).

The main objective of the trial was to convert the wired connections from the control/sensor elements to the control units (UCRs) into wireless links using the devices developed in the project. During the trials a new device, another UCR with wireless functionality, was added to the system. Adding this new device only required a simple modification to the SCADA, stopping the operation for less than one minute. The new device with wireless connectivity was dubbed “UCR-WIZ”.

The new UCR-WIZ was manufactured from the network coordinator called Sensi-c (developed during the project, **Figure 3.3.5-28**).

Figure 3.3.5-28: UCR-WIZ made from Sensi-c network coordinator device

The device is totally compatible with the current UCRs, both physically (fieldbus connectors) and functionally; therefore it can be integrated into the RELIA system by connecting it directly to the fieldbus, and it is also identified by the SCADA as a conventional UCR (**Figure 3.3.5-29**).

As a wireless node, to which the sensors are connected, the universal wireless node called Sensi-s (also developed on the project) has been used. This ZigBee node establishes a wireless link with the coordinator and, by means of an internal protocol, it sends the values received from the attached sensors to the coordinator. Other parameters related with the wireless network (i.e. signal power, network ID, etc.) and internal parameters of the node (i.e. power consumption, battery voltage, etc.) can be sent to the coordinator as well.

Figure 3.3.5-29: SENSI-S adapted for RELIA sensor and control elements connectorization

During the trials, the wireless node was connected to an anemometer and its functionality was checked at several points along three roadways. The measurement points were separated by a linear distance of 10 meters along the roadway axis, close to the tunnel side (approx. 0,3 meters from the wall), approx. 1,5 meters high and alternating between tunnel sides from one measurement to the next. The orientation of the ZigBee node was, as with the coordinator, parallel to the tunnel side. The test was done with metal obstacles and the fans and other power elements switched on (**Figure 3.3.5-30**).

Figure 3.3.5-30: Metal obstacles in curved (left) and under development (right) roadways

Finally the coverage area shown in **Figure 3.3.5-31** was obtained with only one ZigBee access point (UCR-WIZ).

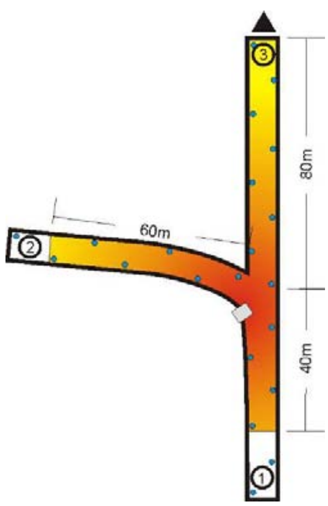


Figure 3.3.5-31: ZigBee area with reliable wireless link for sensor monitoring.

The new devices, which form the rest of the system, are to be monitored remotely from the SCADA computer placed in the control room (normally located on the surface).

In order to check the complete integration of the new UCR-WIZ into the existing system, a new device called "UCR-ZIGBEE" was added to the SCADA. This allowed the value produced by the anemometer connected to the ZigBee node to be monitored from the control room together with the rest of the wired elements connected to the system. **Figure 3.3.5-32** shows a screenshot of the list of the system variables (values) represented on the SCADA. Red rectangles surround the parameters corresponding to the new ZigBee devices.

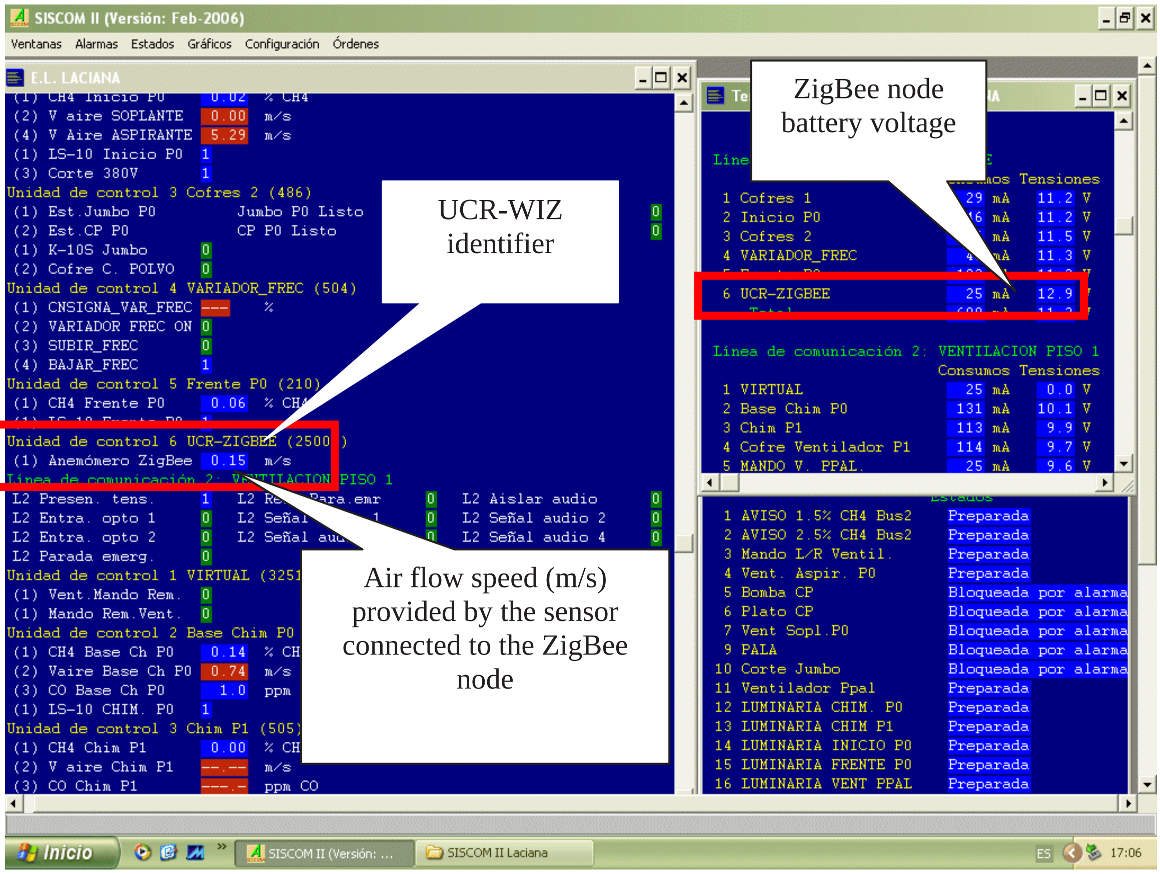


Figure 3.3.5-32: SCADA screenshot integrating the new wireless devices with the rest of elements previously installed in the system

Test of wireless sensors for climatic/ventilation parameters monitoring

The underground tests were carried out in Guido historical coal mine Zabrze (Poland)in two series. First series was conducted in Q4 2007 with preliminary revision of sensors developed in WP2. In order to verify their correct RF design and performance various test areas of level -320m of Guido mine were selected. During these tests the developed ZigBee solution was tried out in point to point configuration. The devices were operating correctly even in harsh propagation conditions present in coal storage reservoir area (as it was described in 5th six-monthly report).

Further trials were carried out in first semester of 2008 with a batch of final revision prototypes (see **Figure 3.3.5-33**). The main aim of these trials was to verify the wireless network performance and collect information regarding optimal parameters for deployment of sensor nodes such as their position within the cross section of the workings, aerial polarity, and location of the packet repeating nodes (routers). The sensors used for that purpose were for measurement of air quality and ventilation parameters. In particular temperature, humidity and pressure difference sensors were used.

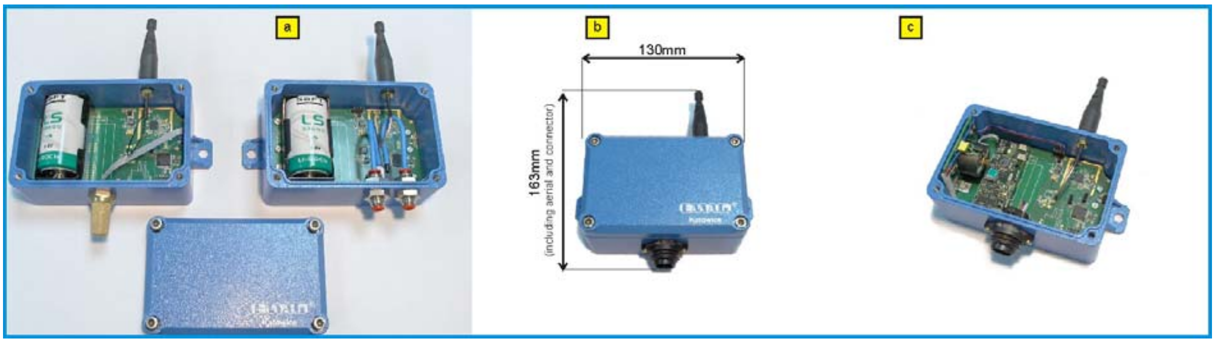


Figure 3.3.5-33: Prototype ZigBee devices – a) sensors, b) enclosure dimensions, c) sink node

Initial trials with final revision of hardware had to verify reliable operation of individual sensors in various underground conditions (see **figure 3.3.5-34**) characterised by harsh propagation conditions i.e. close proximity to metal structures (coupling / multipath) and high power electrical equipment (high EMI). In all mentioned conditions their operation was found to be reliable.

Figure 3.3.5-34: Prototype ZigBee sensors – trials in various conditions

Network performance tests

Next trials were conducted in small network configuration in order to observe behaviour of ZigBee sensor network in a variety of scenarios. First network tests took place in the same coal storage reservoir area. In these severe conditions behaviour of a simple wireless network was studied and methods to improve the performance were analysed.

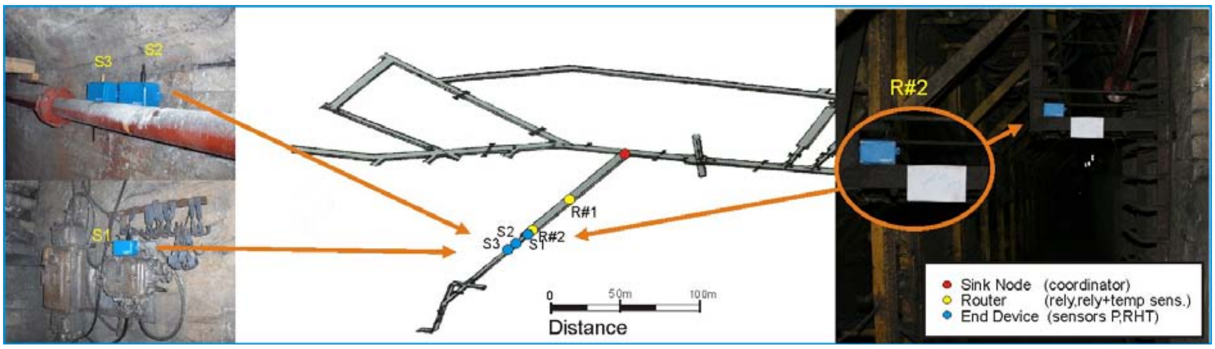


Figure 3.3.5-35: ZigBee network trials in coal reservoir area

Final configuration (**Figure 3.3.5-35**) employing two routers enabled radio coverage within the entire area of coal storage reservoir and in neighbouring section (approx. 100m away from the sink node). Stable network operation was observed with average packet error rate <10%. Later on, a number of trials with wireless network operating in repeater chain configuration were carried out in ventilation gallery and longwall area. The primary goal was to deploy a repeater chain towards the longwall area to collect measurements from sensors located in that area. The sink node used in course those tests was equipped with modem and connected to the surface via mine telephone line. These arrangements facilitated remote data logging in the PABX room of GUIDO mine (see **Figure 3.3.5-36**).

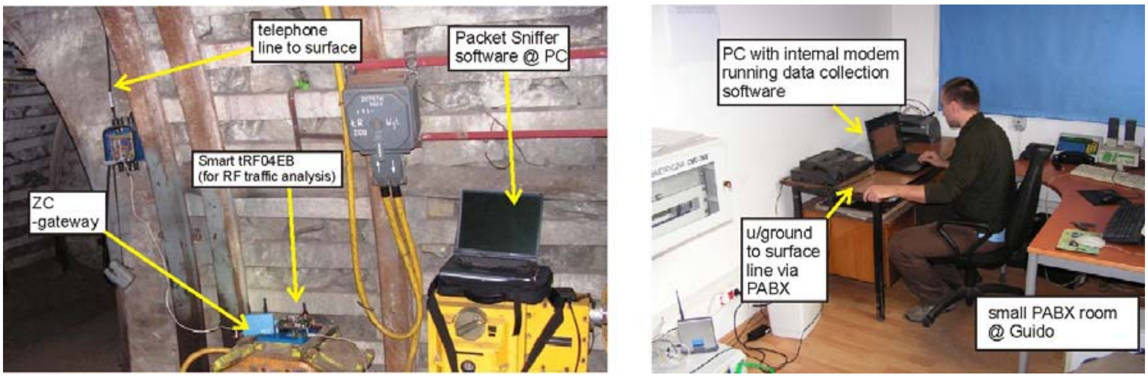


Figure 3.3.5-36: Underground to surface connection arranged for tests of long repeater chain

The network was configured with nonstandard stack profile and deployed with five router nodes chain to ensure reliable link with the remote sensors (**Figure 3.3.5-37**). A few layouts with different distances between nodes were tried out. Finally network survivability was tested with simulated link breaks – router power down.

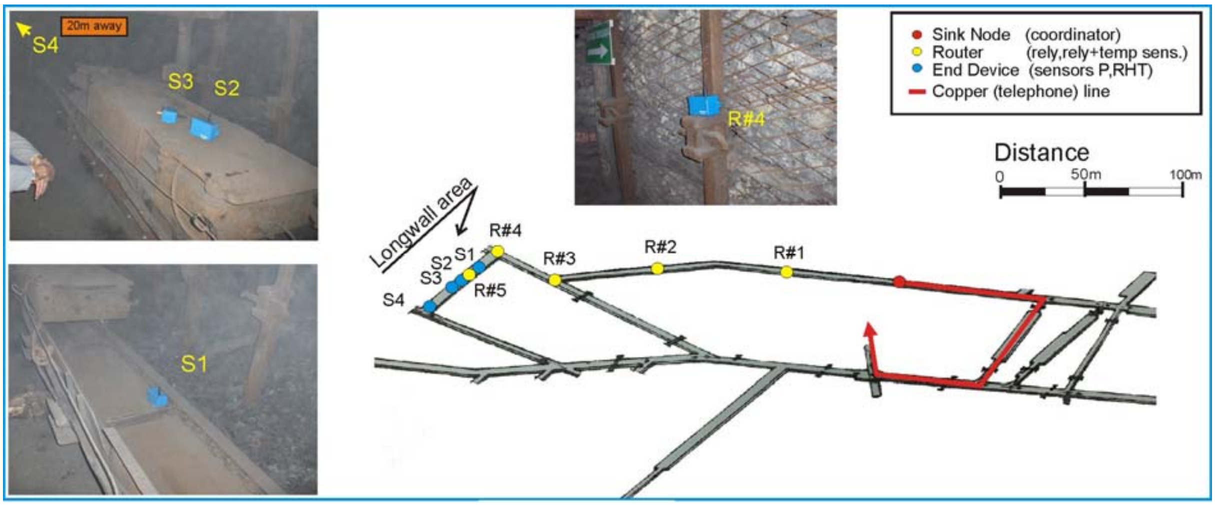


Figure 3.3.5-37: Tests of ZigBee network in long repeater chain configuration

It was concluded that for reliable operation of the network safeguarding a significant link budget margin is required because of noticeable packet error rate aggregation effect. More convenient solution therefore would employ router nodes with RF power amplifiers which, as 'mains' powered, would afford higher power supply requirements.

3.3.5.3 Installation and trials of Personal Area Networks (Activities Task 5.3)

The trials of the devices developed during the project for personnel tracking and guidance were carried out in Laciana Labours School (property of "Fundación Santa Bárbara"), located in León (Spain). The selected location for the trials consists of a straight tunnel 260 metres long (from the entrance to the development face located at the end).

During the tests, the following devices were used:

- A Sensi-c ZigBee coordinator device: Developed under T2.3 of the project, this device has been slightly modified for the trials, replacing the original ZigBee module that had a maximum transmission power of +5dBm by a new higher power version. This should increase the range.
- A directional aerial: The new high power ZigBee module assembled on the Sensi-c board allows the connection of an external aerial. A directional yagi aerial with +18 dBi gain has been used during the tests.
- 3 Sensi-s universal ZigBee nodes. These devices were developed in T2.1. One of them, the same as the coordinator, was modified replacing the original ZigBee module with a new one.

This type of module is capable of transmitting up to +18dBm of output power, but in this case, it incorporates a SMD dipole antenna (+4dBi). The other two nodes were integrated with a PCB intended for tracking and guidance purposes (called TORIENT-V01, see more detail on D4.6), conserving the original ZigBee module with +5dBm of maximum transmission power (**Figure 3.3.5-38**).

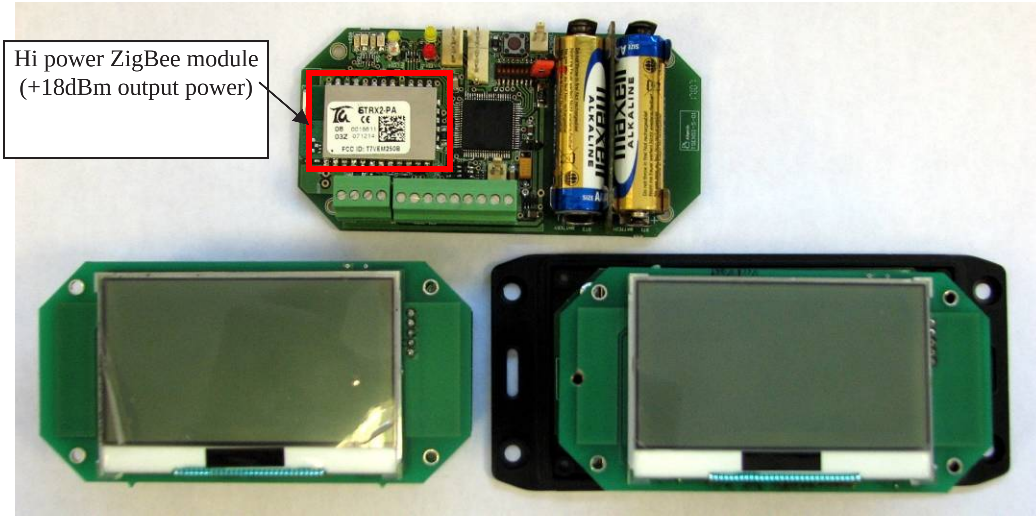


Figure 3.3.5-38: ZigBee nodes used during the trials. One of them incorporates a high power ZigBee module (top), the others (bottom) were assembled with a tracking and guidance PCB (TORIENT-V01).

- A PC connected to the ZigBee coordinator: In order to gather the data provided by the nodes, the Sensi-C (network coordinator) was connected to a PC by means of an RS485 connection.
- A beta version software application installed into the PC: This application developed in C#, provides i) an interface based on windows forms to simplify the network configuration, ii) the interpretation of the coordinator communication protocol, iii) a database link to save both the nodes data and parameters (signal strength and link quality) and iv) a graphical representation of the estimated location of the nodes along the tunnel by means of processing the signal strength according to the propagation model analyzed on T4.6.

During the tests, the network coordinator (Sensi-c) with the directional aerial facing into the tunnel) and the PC were placed just in the tunnel entrance. The nodes, assembled with the tracking and guidance board, were placed at different points along the first 180 metres of the tunnel, and the node that contained the high power ZigBee module was placed in the last segment of the tunnel (from metre 180 to the end). This allowed assessment of the maximum link distance using the high power modules.

Once the coordinator was connected to the aerial and the PC, the software application set the network parameters using the graphical user interface.

When the network was established the nodes located inside the tunnel started sending data. The coordinator polls the detected nodes periodically and returns a message to the PC showing both the RSSI and the LQI.

The PC application adds the new nodes found in the network to the database and updates the parameters of those nodes that have been previously added. This data is also shown on the screen in real time (**Figure 3.3.5-39**).

According to the data presented in the table at the moment when the screenshot was taken, the second node had been detected by the coordinator. However there was no information available about the received signal, node name and LQI (a default value of 100 dBm is shown as signal received power). Accordingly the system cannot calculate the estimated distance from the coordinator to the node and the graphical representation shows the node at 0 position. In the case of the other two modules (situated at the first and third positions in the table), information about the signal strength and link quality has been received. The RSSI value is processed according to the propagation model obtained from the research performed in T4.6. This processing aims to estimate the distance from the coordinator to the node, showing the result in the PC application window.

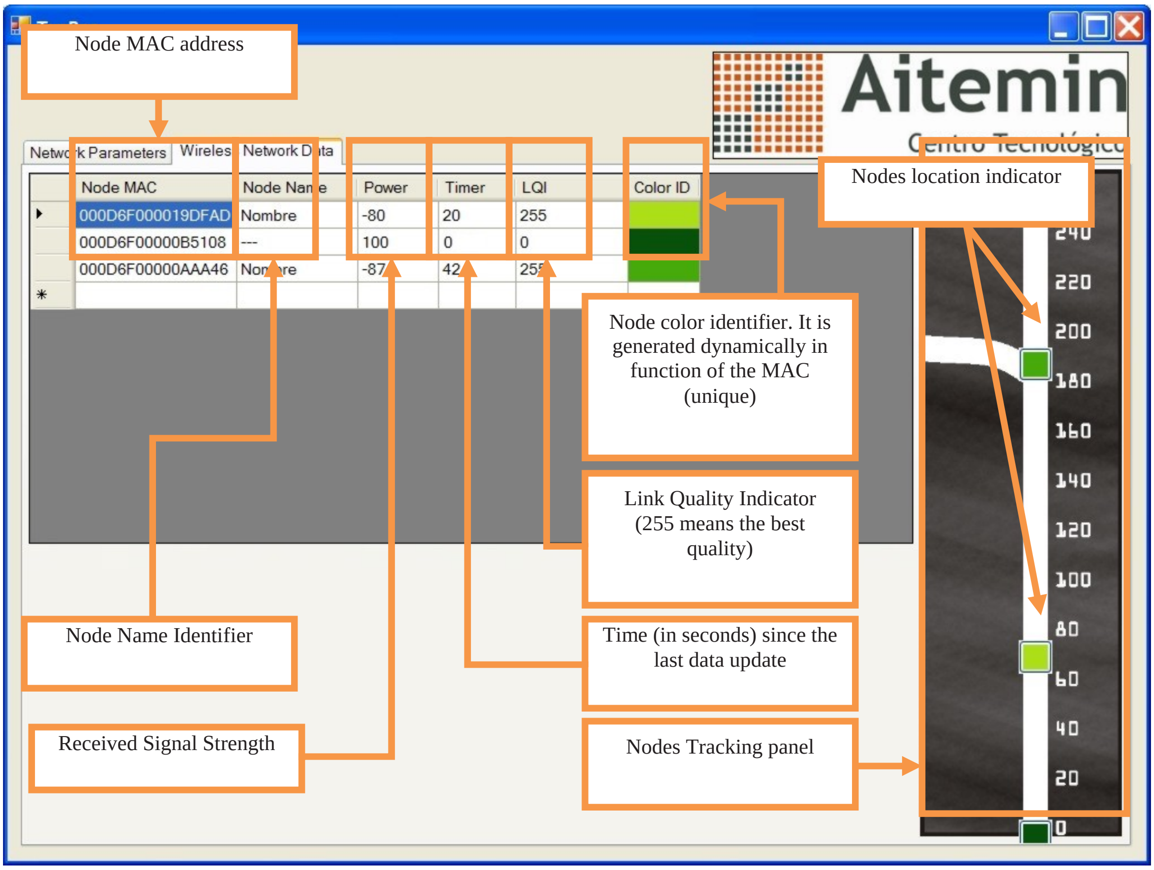


Figure 3.3.5-39: Nodes signal information and location screen

The maximum link distance using the standard modules (+5dBm output power) assuring a continuous communication was about 180 meters (see T4.6 for more details). The use of high power ZigBee modules allows longer link distances. During the trials, the node with high power transceiver was located in different positions up to the development face (just over the stone wall situated at 260 metres to the coordinator). Depending on the obstacles and the aerial orientation, received signal strength between -80dBm and -87dBm was measured and, taking into account that the reception sensibility of this kind of modules is -97dBm, more than 300 meters of coverage area in larger tunnels is expected.

Personal Monitoring Sensors Trials

A series of tests of personal area network components developed in WP4–were carried out at level -320m of Guido mine Poland. The tests were intended to practically verify operation of wireless personal area networks in underground conditions. The sensors, hubs and gateway devices were tried out in different configurations. Special attention was paid to operation on wireless heart rate sensors with regard to perspectives of their soon commercialisation.

General assumption was to test operation of the sensors and sensor hubs in network congestion situation. Main purpose of such tests was to prove reliable multi-user operation in a shared area. Additionally co-existence with WLAN network as the potential 'high power' interferer and wireless headset connection was tested. The personal area network devices which were subjected to underground trials are shown in **Figure 3.3.5-40**.

For the test configuration two wireless heart rate sensors HRM-1 were used. One heart rate sensor was logged to the LCD equipped sensor hub whilst the other nodes were logged to WLAN enabled TRX-WISM hub (forming the second larger PAN network). The remaining sensor nodes were used for simulation of 'network congestion' by periodically sending temperature value in 1s intervals. As jamming sensors three HRM-1 sensor boards one TRX-NRF1 board and one complete environmental parameter sensor equipped with SHT sensor were used. Wireless LAN infrastructure was deployed with use of 3 commercial Linksys WRT54GL WLAN access points with alternative firmware (DD WRT). For the tests (**Figure 3.3.5-41)** they were located in 100m intervals along the ventilation gallery and configured in Wireless Distribution System connection mode. The output power for WLAN was set to maximum level of 251mW (feature enabled by alternative firmware).

Figure 3.3.5-40: Personal area network devices used during the tests in Guido mine

Figure 3.3.5-41: Supplementary WLAN equipment used for the underground tests

The two PAN networks (**Figure 3.3.5-42**) were carried along that area at the same. The readouts from first HRM-1 sensor were observed at the LCD of the hub while readouts from the second HRM-1 sensor and the temperature sensors were transmitted by TRX-WISM based hub to the remote laptop PC with WLAN.

To provide additional source of interference the two persons carrying the heart rate sensors were constantly communicating with UNO-01 wireless headsets (operating at 10dBm).

During these tests no interference were observed. The transmission was uninterrupted and all the readouts were continuously refreshed in 1 second intervals.

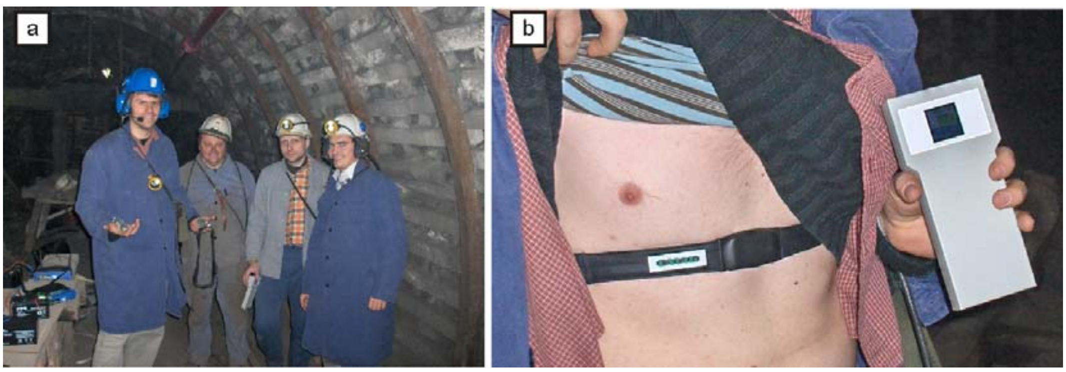


Figure 3.3.5-42: a) the two personal area networks , b) HRM-1 sensor and LCD equipped hub

The test results indicated that embedded protocol features, which provide automatic acknowledgement and retransmission combined with proprietary adaptive frequency hoping scheme, ensured reliable operation even during the simulated network congestion conditions.

Underground Tracking System Trials

The underground tracking system that was developed under T4.6 was tested out during the final operational trials phase of the project. This system comprising 40 nodes, developed using EmberZNet technology, was installed at the CSM Test Mine, as discussed earlier. In order to fully examine the network performance it was decided that a large network (>30 nodes) would be required. Furthermore, ‘worst’ case conditions that an underground mine tracking system would ideally be required to meet as a minimum from an operational point of view were also identified. These were identified as follows:

1. Group of personnel – Large number of nodes passing single ZigBee router, or reading station, (‘Zone’) over short period of time [Large volume, low speed]
2. Small Vehicle – Small number of nodes passing ‘zone’ at speed e.g. travelling in utility vehicle [Moderate volume, high speed]
3. Loco/train – Large number of nodes passing zone at speed e.g. travelling on underground loco [Large volume, high speed]

The mobile devices (MDs) polling (or timing) interval, which is the interval at which each MD will wake-up and look for a new zone, or ZR (ZigBee Router) device, can be adjusted for each MD. For the purposes of testing, reducing the time interval represents the speed at which MDs can be detected. Taking into consideration the performance requirements as defined above it was decided to conduct two sets of tests that attempt to represent these scenarios. The first set using the mine wide network installed at the CSM Test Mine, with the mobile devices polling interval set to 15 seconds, and the second set using six zones and repeating the tests with different polling intervals for every MD, from 10 seconds down to 5 seconds and finally 3 seconds. The shorter time intervals represented the travelling at high-speed requirements. **Figure 3.3.5-43** below shows the routes taken for each set of tests against the layout of the zones at the test mine.

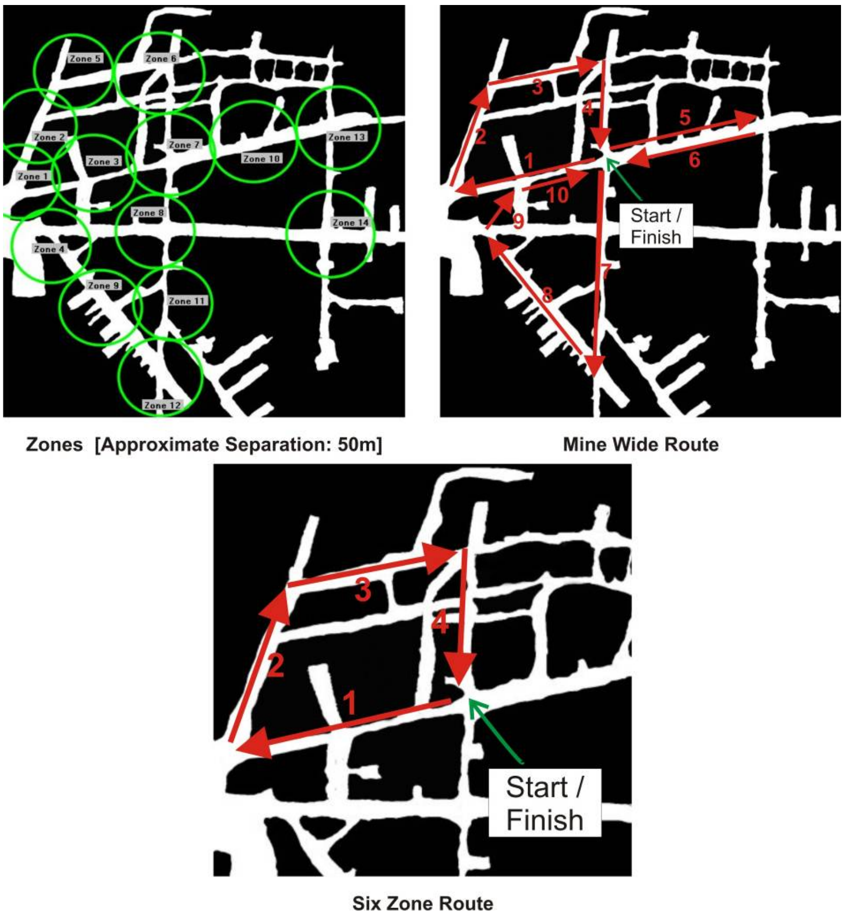


Figure 3.3.5-43: Underground Tracking System Test – Routes Measured

Results

The results were obtained for each set of tests by travelling through the pre-determined routes (mine-wide and six-zones) and recording the location of each MD as it travelled around the network. The location was stored against a time stamp, to the nearest second, in the database. Several measurements where taken for each set of data, and increasing the number of MDs each time starting from 1 device. The data was then processed to determine various performance indicators. These are described below:

1. *Mean Average* – This is the mean average of the polling interval between every device as it is received at the gateway. This was recorded for each measurement (increasing number of MDs). This will vary as the number of transmission retries increases. The network will perform up to 3 retries if a channel is busy. Therefore the polling interval seen at the gateway will vary due to this. This can cause either a decrease or increase to the mean average as a delay during one poling (or time) interval will shorten the time until the next.
2. *Standard Deviation* – The standard deviation better represents the network error. A small number of network retries will cause the mean time interval to adjust. A small standard deviation indicates that again a number of retries have occurred, whereas a large standard deviation indicates network failure due to mobile device polls being missed.
3. *Success Rate* – The success rate is a performance metric of the application as opposed to the network itself, although they are directly related. The success rate is determined by calculating how many MDs have passed through all zones (ZRs). 100% indicates all MDs have passed through all zones. It does not measure network error in itself. For example, if the polling interval is set too high and hence the delay in the MD waking up during travelling between zones is too long, or if the MD transmission fails, zones will be missed.

The mine wide results with MD polling interval set to 15 seconds is shown below in **Figure 3.3.5-44**. The results for the six zone measurement sets with MD polling intervals set to 10, 5 and 3 seconds are shown in **Figures 3.3.5-45, -46 and -47** respectively.

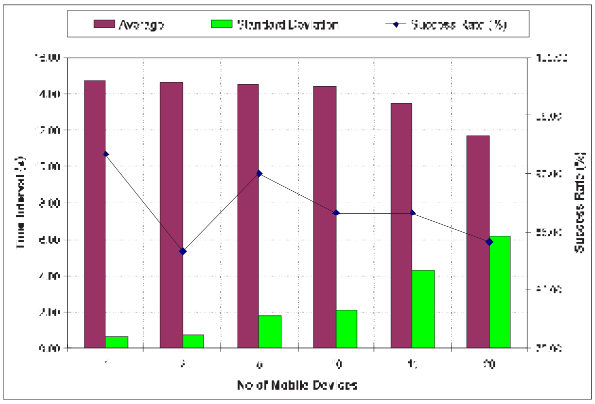


Figure 3.3.5-44: Test Results – Mine wide (MD polling at 15 seconds)

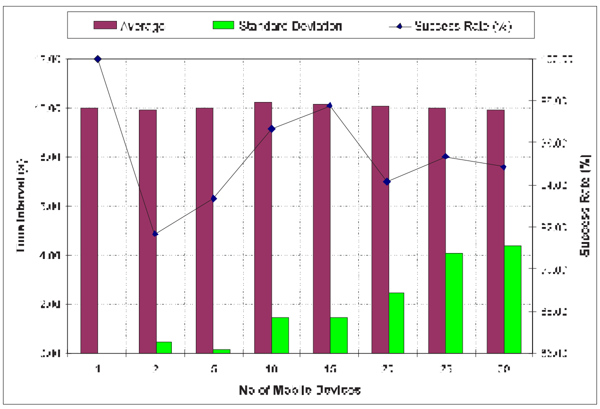


Figure : 3.3.5-45: Test Results – Six zones (MD polling interval at 10 seconds)

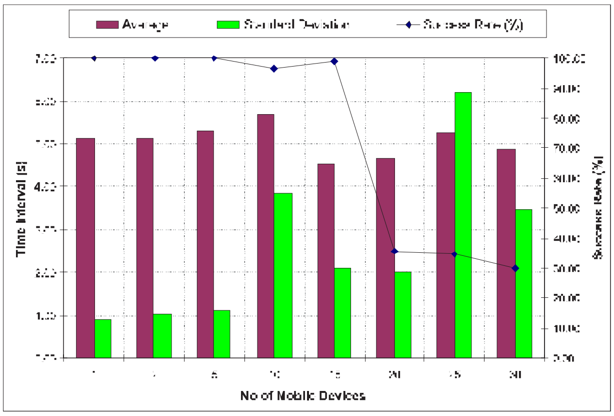


Figure 3.3.5-46: Test Results – Six zones (MD polling interval at 5 seconds)

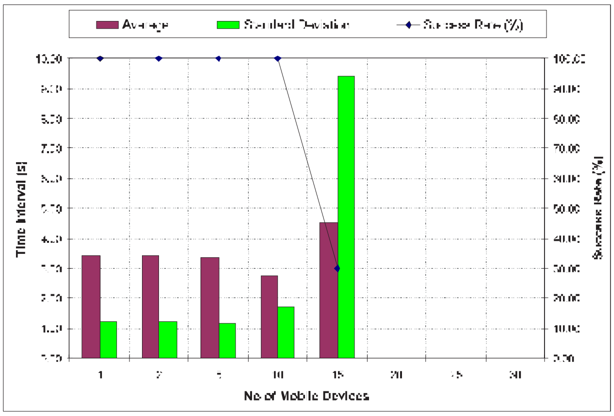


Figure 3.3.5-47: Test Results – Six zones (MD polling interval at 3 seconds)

Discussion

The results have shown that to achieve the 100% success rate (capture all MDs in every zone) the polling interval needs to be 10 seconds or less. Whilst the polling interval of 15 seconds should be low enough to allow the MDs to be detected within the 50m nominal spacing, for example, if a typical walking pace is 5km/h (or 1.4m/s) the distance covered in 15 seconds would be 21m. However, another factor is that the transmission power of each of the MD devices was at the maximum (+3dBm), where in some situations the devices had three ZRs within range at one time, thus it would be possible to miss zones if the detection was picking up the adjacent zone opposed to the current. It was observed that increasing the polling interval increased the success rate, but in practice the transmission power should also be reduced to also alleviate this effect.

During the six-zone set of measurements a relatively robust performance was shown overall using 10 second polling intervals from 1 through to all 30 mobile device, with also a high success rate maintained at the higher number of nodes. Again, lowering the MDs transmission power would suggest that a better success rate could be achieved. Lowering the polling interval to 5 seconds demonstrated a very high success rate up to 15 devices. However, beyond this point both the success rate significantly decreased along with significant increase in the standard deviation of the polling interval, thus indicating network failure. Again similar results were observed using 3 second polling interval where a 100% performance was achieved up to 10 devices, however, this dramatically dropped off at 15 devices and completely failed beyond that point. It was clearly shown that there is a distinct relationship between the number of devices and the polling interval.

Comparing these results with the originally defined 'worst case' requirements has shown that the first two conditions, i.e. #1 large volume at low speed, and #2 moderate volume at high speed can be met. However, the third condition #3 large volume at high speed would need further work. Initial thoughts are redesigning the network topology to include intermediary ZR devices to act as mobile zones sending large quantities of the MD's location data on the move. Also an adaptive polling interval would help improve the network performance, where the traffic could be significantly reduced at times where there are no changes to the location (or network topology) occurring.

3.4 CONCLUSIONS

This section indicates the achievements made.

3.4.1 Basic research for enhanced and fail-safe open wireless underground communications (Conclusions WP1)

Valuable basic results have been achieved and supplied to the other WP's, which were very useful for the further efficient development work.

3.4.1.1 Exploring the propagation of electromagnetic waves (Task 1.1)

Extensive tests were made to quantify the propagation of electromagnetic waves in underground mines and tunnels. Classical tunnel attenuation measurement and field mapping techniques were used, with CW 'pure' transmission at 2.3GHz and 5.8GHz including assessing coverage around items of mining equipment and plant. Tests were carried out at in a disused rail tunnel, a disused hard rock mine and in RAGs TBW test mine facility using a range of wireless technology equipment, to evaluate the overall performance in terms of throughput versus range. The measurement results were compared with those dervived from tunnel wave guide theory with reasonable correlation where the theory was appropriate. Measurements were also made of EM propagation at various frequencies through concrete. 2.4GHz was selected for future work. It was concluded that it was feasible to use this technology for through-the-rock transmission for rock stress measurement.

3.4.1.2 Examination of candidate wireless technologies (Task 1.2)

After assessment of several technologies IEEE 802.15.4/Zigbee technology was proposed as the development platform for future low data rate sensing, monitoring and control applications. Additional technology types will be needed to address high data bandwidth applications, as required. Bluetooth was selected for the wireless mines rescue communication link with provision for later upgrade to Ultra Wide Band (UWB) when available. UWB will have enormous potential when it comes to market.

3.4.1.3 Market analysis for smart sensor network technologies (Task 1.3)

Technology platforms were selected and appraised, which are suitable for the underground low power wireless sensor network applications identified within this project, e.g. smart sensor networks and active zonal position tracking systems. The need for development of an active ATEX approved RFID system was identified.

3.4.1.4 Specification of operational criteria for sensor networks (Task 1.4)

Any practical application of (embedded) wireless sensing will need to present a small physical envelope, with minimum mechanical vulnerability. Concerning technology options for compact, microstrip antennas, the Planar Inverted-F Antenna and Electromagnetic Bandgap solutions were identified as being suitable for further development.

3.4.1.5 Researching alternative power supply techniques for smart devices (Task 1.5)

To eliminate the need for external power supply cables and to achieve 'true' wireless performance beyond conventional battery supply, motion power harvesting was selected for further development. Alternative battery types were thoroughly investigated for the m-Comm wireless link and possibilities to redesign circuits to minimise power consumption have been elaborated.

3.4.1.6 Examination of available operating systems for sensor networks (Task 1.6)

Since the operating systems, which appeared to be suitable for the devices and applications to be developed, have been identified and characterised, the further development work within the other WP's could rely on these findings. Technical problems due to selecting not the optimum operating system could be avoided and a higher efficiency of the development work achieved.

3.4.2 Development of smart wireless sensor networks with innovative power supply strategies (Conclusions WP2)

3.4.2.1 Smart wireless sensors for temperature, humidity, pressure, flow-rate, rock stress (Task 2.1)

As results of research work the prototype smart sensors were developed. They are characterised by very low power consumption enabling maintenance-free battery operation up to approximately 5 years. Tests both laboratory as well as in real conditions proved their usefulness for underground applications. The developed prototypes were able to establish high quality communication links and form interference-resilient network even in highly multipath conditions. Self-healing properties of the networks based on the developed wireless sensors were also proved.

Versatility of interfaces made possible to develop sensor devices covering measurement of assumed physical parameters, connect to existing sensors (cable replacement role) and safeguard the future expansion of the developed solutions (by many spare digital and analogue interfaces available). Use of state of the art low power and high performance processing components (dsPIC by Microchip, MSP430 by Texas Instruments) was combined with employing their potential of advanced power management modes. This enabled the desired functionality while maintaining low power operation.

The repeatedly improved wireless Chirp sensors and their necessary base stations worked very successfully and the continuously reworked security software protocols of the Chirp telegrams worked also very successfully. At the end of the project 4 different types of wireless Chirp sensors working with low power of only 100mW were available (inclusive the necessary base stations).

3.4.2.2 Alternative power supply for smart sensors and devices (Task 2.2)

Positive results were achieved with energy scavenging technology converting mechanical energy of vibrations into electricity. The developed device uses voltage generation out of changing magnetic field resulting from moving magnets which impact set of solenoids. The amount of energy which can be supplied by the prototype device was found sufficient, in conjunction with rechargeable batteries acting as an energy reservoir, to power wireless sensors. This can effectively work providing the proper power management mechanisms are applied and the duty cycle of measurements is long enough to collect the sufficient amount of energy.

3.4.2.3 Interface connectors and electronic control units (Task 2.3)

The successful development of the Data Acquisition Gateway device and of interconnection interfaces for low power sensor networks filled the gap between the existing well established mining communication systems and novel solutions based on wireless technologies. The developed devices enable deployment of expandable distributed monitoring and control systems essential for modern mining automation. Wireless data collection will result in significant savings of costs related to replacement of old style cable infrastructure connecting wired sensors to data collecting devices.

3.4.2.4 Development of mobile and stationary intrinsically safe RFID-read and -write equipment (Task 2.4)

Approach for RFID employing LR-WPAN networks has great potential especially in acting double role of location and sensor data acquisition. This concept was positively proved in practice during the tests of prototype zonal location system in Camborne (carried out in WP5). Additionally some emerging LR-WPAN technologies give possibility of pin-point location which can be very advantageous in many applications.

The developed RFID read and write equipment together with the mobile tags use innovative dual band technology which takes extensively advantage of radio propagation in both bands in order to achieve maximum performance for radio identification process. The mobile tags in final revision are characterised by very compact dimensions and low power consumption which make possible low cost (no maintenance for long time) and easy application of personnel and material tracking system

3.4.3 Development of applications for the utilisation of smart wireless sensor networks (Conclusions WP3)

3.4.3.1 Temperature monitoring in the area of conveyor belt drives with sensor networks (Task 3.1)

Statistics indicate that many fires are initiated in the area of belt conveyor drives. Commonly used protection systems based on bimetallic or Curie point switches are triggered only when serious failures occur (which is sometimes too late) and are not always reliable. Continuous monitoring of temperature in the belt drive area in combination with belt slippage has an considrable advantage in early failure detection and makes preventive maintenance possible. The developed solution for monitoring of belt drives has a great potential to enhance both, safety and economical efficiency related to their maintenance.

3.4.3.2 Self-organising networks for advanced monitoring of the infrastructure in mines (Task 3.2)

All developed software enables easy management and data access of ZigBee sensor networks for various applications. The data acquisition system can be easily integrated within existing mining communication infrastructure. The topology of these higher process level applications also permits users to remotely log on the web server using HTTP. Respective developed software offers the possibility to use different types and numbers of remote sensor WSN devices.

3.4.3.3 Monitoring Rock Stress (Task 3.3)

With the application of WSNs also for mechanical rock movements, the advantage of an online-measuring method could be manifested. Additionally the extensive wiring for the up to now copper based sensor equipment belongs to the past.

3.4.3.4 Development of an underground RFID-based navigation and tracking system for machines, material flow and persons (Task 3.4)

Wireless sensor networks are now available, which are suitable for navigation and tracking of personnel and material in different environments of data transmission infrastructures. They were used and tested within tasks 4.6 and 5.2.

3.4.3.5 Wireless Sensors Access with PDA’s (Task 3.5)

Under this task versatile software was written for both, proprietary and for already certified PDA’s with the objective to manage different functions of the WSNs directly on site. By that, the WSN data, which are transmitted to the surface, are made also locally available underground.

3.4.3.6 Gathering and Collation of Operational Data for All Wireless Devices (Task 3.6)

The results of this task are of great importance to design WSN’s and to adopt them to the individual underground conditions and environments in order to avoid disturbances, interferences and malfunctions, thus to guarantee maximum reliability.

3.4.4 Development of personal area networks for tracking, monitoring and guidance under health & safety aspects (Conclusions WP4)

3.4.4.1 Development of smart personnel sensors for health and safety values (Task 4.1)

In order to design a health monitoring system aimed for underground applications personnel, a previous analisys in-depth in order to know which are the most important physiological human parameters to be monitorized was performed. In addition, a overview and study of similar systems existing on the market (aimed to other fields as military) was carried out, getting information about its operation mode, parameters measurement techniques, etc.

The information obtained from the above research was used to design a new health monitoring system according to ATEX, getting an operative prototype of the system suitable to be used in mining applications. This prototype was also designed using the wireless technology researched during the project (specially obtained from results of T4.3 and T4.5), getting a device capable of being integrated into PANs, used by other appications (e.g. enviromental parameters monitoring) also developed along the project.

Although audio interfaces based on throat microphones have been selected as most suitable to mining applications from the point of view of noise cancelling, the feedback provided by rescue team members regarding to its use within high heat and humidity environments shows a suffering neck rash after a period of time. A solution for that will be looked for.

3.4.4.2 Smart personal sensors for environmental values (Task 4.2)

A multi-sensor node including CH_4, O_2, CO and T sensors was developed. Based on two pellistors (a special type of gas sensors) and a single Wheatstone bridge, the CH_4 measurement is taken using very low power resources. With the use of an electrocell for O_2 detecting, low power consuption elements for T^a and CO measurement and time sliced operation, the designed device became suitable to be used in battery powered applications. The integration of a microcontroller including a signal processor core makes easier or even totally automatic the usually complicated and costly calibration and compensation processes. The designed and prototyped device includes wireless connectivity according to the technology developed during tasks T4.3 and T4.5.

An alternative to the developed WSN’s for monitoring the environmental parameters is the use of the m-Comm system in connection with the multi-sensor node. It is capable of multiplexing the sensor data values with the analogue voice in order to send both informations through the same 1 wire cable.

3.4.4.3 Integration of personnel voice communication (Task 4.3)

An electronic module to be integrated into a mining headset has been developed. It is capable of receiving data form the PAN sensors and providing pre-recorded voice warnings to the personnel who is wearing it, about for example, alerts trigger, evacuation process instructions, etc. Thanks to the work performed on T4.5 this module is also capable of acting as PAN to WLAN gateway, providing a bi-directional data path between the headset and backbone communication network, including PAN sensor and digital voice data exchange.

Continuing with the work developed on RFC-CR-03003 project, a mixed communication interface for machinery data and voice has been developed. It allows keeping the machinery operator continuously in contact with the main voice communication line of the mine as well as providing information about the machinery parameters to the monitoring and control systems.

An analysis about the integration of wireless technology in m-Comm system has been perfomed, studing candidate technologies as well as its possible interferences with the existing wired system. The pros and cons of each one have been identified.

3.4.4.4 Wireless adapting of mine rescue communication systems for hands-free operation (Task 4.4)

Having as main goal the adaptation of m-Comm system to be capable of supporting communication based on wireless devices, the key points to achieve that purpose were analised during this task. New electronic solutions to solve the weak points of the current wired system as well as the new ones introduced by the use of wireless technologies have been presented and prototype wireless m-Comm units produced. Some of them are based on the introduction of digital elemens to the current analog design in order to solve issues regarding specially with EM noise, squelch threadholds, tone generation, etc.

Desing considerations regarding to ATEX standard were taken into account as well as an intuitive operation mode and confortable external elements as PTT buttons or audio transducers (microphone and earphone).

3.4.4.5 Development of a personal communication interface for WLAN access (Task 4.5)

A roadway amplifier including wireless voice connectivity has been developed. The base design was developed during the project RFC-CR-03003 and several improvements have been added to it, being the most significant, the capacity of establish wireless links with portable voice devices under its coverage area. The technology selected for that purpose was Bluetooth, allowing the device to be paired with any headset of the market which supports that standard. In addition, this enhanced roadway amplifier is totally compatible with the current systems already installed in mines (based on RELIA-2000), acting as gateway between the current analogue voice trunk lines and the new digital portable wireless devices.

In order to make easier the integration of the PAN technologies developed during the project with the already existing monitoring and control systems, a PAN to WLAN gateway device was developed. It allows the easy integration of PAN based devices as sensors, actuators, etc. with the trunk communication backbone by means of a wireless connection based on the usually used LAN infrastructures.

3.4.4.6 Personnel tracking and guidance in critical situations (Task 4.6)

A tracking and guidance system based on ZigBee wireless technology has been developed. This includes a tracking software including Data Base storage as well as the portable devices that provide to the global system the position and status of the personnel who is wearing them. In the opposite way, these portable devices are capable of receiving information from the system regarding to possible emergency situations and providing information to the person about the action to be performed, including guidance towards the next refuge or way out through safe paths.

Further researches in the field of ZigBee signal propagation across the tunnel has shown that the accuracy of the location and tracking system can be improved by means of using the results obtained from the mathematic expression obtained from the propagation model study.

3.4.5 Operational trials programme in underground mines (Conclusions WP5)

3.4.5.1 Test-run, trials of Mines Rescue communications system in underground mines (Task 5.1)

In conclusion, the initial objectives and aims of the mines rescue communication aspects of the project were fully achieved and with better results than expected. The security of the wireless voice link within 10 m range of the portable forward ‘hub’ has been tested in a wide range of confined and underground spaces. The results demonstrated that there is a higher than 90% probability of maintaining communications up to 15m and 95% up to 10 m. No wireless system can give a 100% availability figure given the unknown situations and environments that rescue communications units are expected to encounter. Semi-flooded mines or temperatures above 50 ºC would be regarded as an extreme condition for the wireless m-Comm.

RMT’s investigation into power supply for wireless systems concluded that it is more feasible to reduce the power demand than to increase current battery energy storage capacity. As a result, conventional power packs were adopted in the wireless m-Comm but with more use made of very lower power electronics components. It is envisaged that in the next update of the wireless modules further power efficiency improvements will have been made. Harvesting power from the environment is not an option for wireless m-Comm.

The practical aspects of the prototype mines rescue communications system were also tested and judged by a cross section of would-be users to be good. The Ni MH battery pack provided a typical operational life of over 12 hours. Ni MH still has the longer cell life with 800 to 1000 charge discharge cycles and proved more suitable for mining applications. Water proof microphone, speaker and switches were all necessary for underground operations as was minimum use of external connecting cables.

In operational trials, the wireless m-Comm system functioned as expected even with naive operators. Limiting the mobile unit to press-to-talk, functionally the same as for the handheld unit, made the wireless link operationally more robust and ensured inclusion of all parties on the system to all conversations.

In researching the developments in wireless technologies, RMT identified the potential of Ultra Wide Bandwidth. UWB wireless systems would provide better coverage as well as automatic distance information in mining applications. A single UWB product was tested in simulated mine conditions and found to be highly effective. The PulsON 200 units from Time Domain Inc., were configured to demonstrate: a) distance against data throughput b), distance measurement between two devices and c) angle of arrival of signal. The only drawback, other than the lack of commercial UWB products, was the high power demand of the receiver section of the unit. It was reported by the manufacturer that the high current demand from the front-end analogue-to-digital section of the multi functional unit was old technology and the power requirement would drop with the next generation.

The incorporation of wireless communication capability into the roadway amplifier has produced benefits to the system from a functional and safety perspective. The use of portable devices for audio communication, based on headset or throat microphones, allows most of the environmental noise usually produced by the machinery in working areas to be cancelled. It also permits the workers to be in continuous contact with the global communication system, allowing voice communication even from the actual working site (they do not need go up to the intercom).

Regarding safety, the use of both a roadway amplifier and portable wireless devices with integrated batteries permits its use in emergency situations even after a general failure in the main power supply. Including a personal wireless device in the workers' equipment assures the reception by the personnel of warnings and alarms sent through the voice communication system in emergency situations. The selection of Bluetooth as the wireless technology for voice communication permits the identification of individual portable devices connected to an access point (intercom). This information is very useful in emergency or evacuation situations.

3.4.5.2 Installation and trials of Smart Sensor Networks (Task 5.2)

The extensive trials in the training mine (TBW) showed that the wireless Chirp sensors (inclusive their base stations) are able to work very successfully in the rough area of a hard coal mine underground.

Within all areas underground, where it occurs that electric lines are often destroyed, the wireless sensors can reduce the down-time substantially (e.g. in the junction area of the longwall face and the roadway). A lot of different application types of wireless sensors are conceivable. DMT for example improved the wireless sensor modules therefore that measured values from anchor measuring sensors are taken up and can be transmitted. All measured values, which are determined by means of strain gauges, can be processed by this module.

The main advantage of the wireless sensors is the flexibility (with the integrated battery a wireless sensor can be brought very simply from location A to location B – no voltage supply by cables is necessary). Further advantages are relatively simple start-up (learning mode with start-up buttom to register the sensor at an I/O unit) and the omission of maintenance of cables.

The wireless mesh smart sensor system that was developed under WP3 has been trialled in this task. Initial trials were carried out using EmberZNet/EmberNet technology in order to examine the network performance, particularly in regard to improving the transmission using omni-directional gain antennas. The smart sensor system was developed using EmberZNet / ZigBee technology. The effect of a break in communication was simulated (e.g. a roof rock fall occurring), where the packets are sent across other multiple-routes and the network sends data via the lowest cost route. The ‘cost’ is established by the network stack through comparing signal strength, link quality and number of hops. Also, with the availability of multiple vendors of ZigBee and EmberZNet technology, trials were conducted comparing a selection of technology options available using different antenna configurations. Finally, the actual smart sensor network system, which was developed under WP3, was also tested out, particularly examining issues of actual sensor interfaces (PRT and barometric pressure), determining measurement accuracy of the EM250 chip, and enhancing the application functionality such as providing real-time data display and scalability.

The new SENSI devices can be perfectly integrated into the existing monitoring and control systems, providing wireless connectivity, and consequently all its associated benefits. In the studied area, a single UCR-WIZ would be enough to monitor and control the 15 elements located inside, replacing up to 5 wired UCRs currently installed, more than 200 meters of heavy duty bus cable and 38 robust connectors. The integration and compatibility of the new technology with the monitoring system has been also proved, without needing to perform any modification to the SCADA. The way the data is sent from the sensor elements to the control units and vice versa is totally transparent to the monitoring software, simplifying the coexistence of the two kinds of technologies at the same time in the same installation.

Tests of prototype wireless ZigBee sensors carried out in Guido mine helped to determine the performance of developed devices in real underground conditions. Some of the worst-case conditions were identified and the appropriate means to maintain reliable operation were studied. The results confirmed proper design of sensor and sink nodes and proved their predictable and reliable operation. Performance trials of simple networks in various configurations indicated robustness of the network stack software and proved self healing properties of the network. The developed wireless sensor nodes were found appropriate to operate as end devices and short distance packet forwarding FFDs. The sink-node gateway unit supports wired communication interface compatible with centrally powered systems common in Polish mining and has the advantage to be powered over the single transmission line. For wireless nodes maximum usable range (i.e. at reasonable PER ensuring stable network operation) was between 70-90m (depending on the conditions). However, it was also observed that some network configurations would benefit from use of power amplified intermediate nodes that would allow achieving longer distances between nodes. Such approach can be more cost efficient as there is reduced number of FFDs required and also more reliable (less impact of PER accumulation).

The active RFID transponders and their necessary transmitting / receiving stations (active RFID equipment) have been repeatedly improved during the project. At the end of the project 6 transponders (final prototype generation, ready for series production) and 2 transceiver stations with fibre optic interface were available. Five of the six transponders are equipped with an LS14250-battery (8 years life time) and 1 particularly miniaturised transponder with CR2430-button cell (2-3 years life time).

The extensive trials in the training mine (TBW) showed that the developed transponders (inclusive their transmitting / receiving stations) are able to work very successfully in the rough area of an underground hard coal mine.

At the end of the project the development of this active RFID equipment reached the series-production readiness. However, an ATEX permission has not been accomplished within the project. This still needs to be done in order to use it in an operating mine.

3.4.5.3 Installation and trials of Personal Area Networks (Task 5.3)

The use of the wireless ZigBee technology for tracking and guidance systems has been proved, obtaining good results as far as coverage area, personnel identification and location is concerned. From the point of view of the hardware, the required elements necessary to perform a complete tracking and guidance system has been developed during the project, resulting in reliable and portable devices as well as a network coordinator, i.e. a gateway between the portable devices and the SCADA. The embedded firmware allows the information received from the wireless network to be shown on the portable devices’ screen and the values from sensor elements to be sent to the wireless network, performing all the expected functionally. The application installed in the PC used during the trials is only a prototype (beta version) of a future commercial adaptation that can be integrated into the existing

SCADA systems.

The system concept, discussed in T4.6, was developed using a standards-based wireless mesh networking technology called EmberZNet (ZigBee Pro ratified standard). The aim of the trials programme was to examine the performance of the network using a large scale network (>30 nodes) operating within a typical underground environment. The results have shown successful and robust operation of the network with up to 30 mobile devices (MDs) operating across a mesh network comprising several ZigBee router (ZR) nodes. The results have been compared against pre-defined ideal (or worst case) operational requirements of the network. The results have been favourable in operating against such conditions as achieving large volume of MDs against a low travelling speed and also moderate volume against high speed detection. However, the results have shown that there are a number of issues to be resolved in achieving consistent location detection of a large volume of devices at high speed. There is a distinct relationship between MD polling interval and the increase in number of MDs. Therefore, there would still be further development required in order to achieve certain ‘worst case’ underground mine operation requirements.

In addition to this, wireless nodes with bidirectional features have been developed allowing the transmission of personnel status data and providing guidance to their bearers in case of emergency.

Further trials in order to prove that concepts were also performed, including the implementation of algorithms capable of predicting the distance from the node to the network coordinator based on the information provided by the received signal strength and results obtained after analyzing the signal propagation model through the tunnel.

Positive results were obtained from these trials, having a robust bidirectional link even in large link distances and a significant improvement of the location accuracy of the system using the propagation model algorithms.

An ultra low power solution for heart rate monitoring was developed and positively verified during underground field trials. The tests proved correct operation of the developed wireless sensors for personal area network. The proprietary frequency hoping protocol was found to work reliably even in simulated network congestion conditions. Additionally during the project, the developed wireless heart rate sensors type HRM-1were subjected to verification of their medical accuracy in accredited laboratory of ITAM Zabrze (transl. Institute of Medical Technology and Equipment). They successfully proved compliance with EN 60601-2-27:2006 standard.

3.5 EXPLOITATION AND IMPACT OF THE RESEARCH RESULTS

This section addresses issues related to the exploitation and impact of the research results. It comprises information on:

- actual applications;
- technical and economic potential for the use of the results;
- any possible patent filing;
- publications and conference presentations resulting from the project;
- any other aspects concerning the dissemination of results.

3.5.1 Basic research for enhanced and fail-safe open wireless underground communications (Exploitation WP1)

Mainly, the exploitation of WP1 consists of supplying basic results to the other WP's. Thus the other WP's exploited these results for their more application and product related research and development. However, some of these results would also be useful for other research projets dealing in similar technologies (e.g. wireless technology for automation, etc.).

3.5.1.1 Exploring the propagation of electromagnetic waves (Task 1.1)

A detailed internal report (deliverable 1.1) on the propagation of GHz electromagnetic waves in mines was produced under this Task. This is also available to researchers on other related RFCS projects involving underground radio communications and data transmission. The results of the work on this Task were fundemental to the systems developed during the later stages of the Project.

3.5.1.2 Examination of candidate wireless technologies (Task 1.2)

The identification of Zigbee and Bluetooth as viable and currently available technologies for application in coal mining related distributed sensor networks and voice communications systems respectively was essential to the product developments made in later stages of the Project. One of the most important aspects was the identification of Ultra Wide Band as the most likely technology for future wireless network developments and thus the need to ensure that systems developed under this Project were capable of upgrading to UWB when it eventually becomes commercially available. This was an important factor in the selection of Bluetooth as the basis for voice and low data rate communications in the wireless mines rescue system and should ensure that it can be readily upgraded within the new ATEX certification as technology progresses. These outcomes will be very important to those working on other automation related RFCS project such as NEMAEQ.

3.5.1.3 Market analysis for smart sensor network technologies (Task 1.3)

A tabular analysis of the Wireless Sensor Network (WSN) Technology Development Platform Options avialable during the first period of the project was produced as the main deliverable for this Task (deliverable 1.3). This analysis was valuable for the ongoing work on the Project. However, as the market is rapidly evolving with improvements in the technology, the analysis undertaken for this task has already been superseded. That was an absolute reasonable basis for the development of the products and applications within RAINOW, but can not be taken as basis for new projects without updating.

3.5.1.4 Specification of operational criteria for sensor networks (Task 1.4)

The deliverable for this Task comprised two internal reports, one on characterising interference between Bluetooth, Zigbee and other WiFi systems and one being a Technical Review of Compact and Microstrip Antenna Technologies. Both these reports are available to and will be important for other RFCS researchers including those working on the NEMAEQ project. The interference studies resolved initial concerns over possible interfrence between Bluetooth and other wireless systems provided low power Class 2 Bluetooth version 2 was used, which justified the continued development of the commercial Mines Rescue Communication system under the Project.

3.5.1.5 Researching alternative power supply techniques for smart devices (Task 1.5)

The deliverable for this Task was an internal report on Alternative Power Supply Strategies for Sensor Networks, which is also available to researchers on other RFCS projects. The work on developing ultra low power circuits and battery technology was directly relevent to the product developments undertaken later in the Project. Once again these technologies are developing rapidly and new projects in the field will need to update this work in the light of technical progress in the interim.

3.5.1.6 Examination of available operating systems for sensor networks (Task 1.6)

The results of this Task were fully taken into consideration during system development later in the Project. They are not directly exploitable beyond the Project as they were specific to allowing appropriate design decisions to be made within the later Workpackages.

3.5.1.7 Deliverables of WP1

The deliverables produced within WP1 are listed in Table 3.5.1-1 below.

Deliverable	Type	Task
Report on the results of the propagation of electromagnetic waves in mines	Report	T1.1
Report on the results of the individual capabilities of wireless technologies	Report	T1.2
Market analysis of smart sensors network	Market analysis	T1.3
Layout criteria for smart sensors networks	Specification	T1.4
Alternative power supply strategies	Report	T1.5
Operating systems for sensor networks	Report	T1.6

Table 3.5.1-1: Deliverables produced within WP1

3.5.2 Development of smart wireless sensor networks with innovative power supply strategies (Exploitation WP2)

In addition to the exploitations described below for the individual tasks of WP2, all results have been exploited within WP3, WP4 and WP5. WP2 provided the basic devices needed for the development of WSN applications (WP3), personal area networks (WP4) and for the underground trials (WP5).

3.5.2.1 Smart wireless sensors for temperature, humidity, pressure, flow-rate, rock stress (Task 2.1)

Wireless sensors which were developed during the project can cover a large span of underground measurement applications and provide an efficient way to limit costs related to installation and maintenance of cabling (e.g. in the transient-area between coal face and the gate road) and also costs generated by system down-time (related to cable systems). The prototype devices developed in WP2 were used in subsequent work packages WP3-WP5.

The prototype ultra low power ZigBee sensors will be further optimised and certified according to ATEX within EMAG’s EUREKA (project No11.3943.7). Within the mentioned project the wireless sensors will be further tested in larger scale configuration in semi-permanent network (more than a month of operational underground trials is envisaged). Some solutions resulted from development work were used in ongoing RFCS project NEMAEQ for implementation of longwall equipment monitoring wireless network. Results of tests (performed later on in WP5) indicated the wireless sensors can be perfectly integrated with the existing mining SCADA systems.

As part of dissemination activities a paper ‘Applications of modern wireless communication technologies in mining industry', covering among the others some information with regard to potential application of wireless mesh networking related to work carried out in RAINOW project, was published in 'MIAG' journal No 5/2008 (Journal on Mechanisation and Automation of Mining published by EMAG). An internal seminar 'Wireless smart senor networks' was also held in September 2008 (in EMAG) brushing some aspects of the research work results related to wireless sensors of mesh topology.

3.5.2.2 Alternative power supply for smart sensors and devices (Task 2.2)

It is expected that the developed energy harvester will find application to power autonomous wireless sensor systems on mining machines. Taking into account new achievements in this emerging branch of technology the concept will be further optimised with prospects to get much higher efficiency and enable more power-demanding applications.

3.5.2.3 Interface connectors and electronic control units (Task 2.3)

The developed interconnection devices will be used to expand distributed wireless networks for monitoring, control and communications in underground workings. The Data Acquisition Gateway which is already ATEX certified can interconnect novel wireless sensor and actuator devices, with use of gateways, through FO based backbone. Apart from telemetry and control applications also the VOIP (Voice over IP) communication is possible. The ZigBee gateways are capable to route data from WSN to fieldbus-based and centrally powered systems. In case of the later deployment of Zone 0 /20 monitoring applications would also be possible.

3.5.2.4 Development of mobile and stationary intrinsically safe RFID-read and -write equipment (Task 2.4)

The developed RFID equipment and ideas were used successfully in the subsequent workpackages.

Use of novel approach of RFID solution employing 3D LF wake and VHF answering scheme will be an efficient way to deploy material management systems for mining. Small size of the tag devices and long battery life will result in low maintenance cost and make the concept financially feasible what should lead in short time in application in European mines (see WP5).

The complementary approach using LR-WSN can benefit from acting the double role of telemetry system gathering vital data from distributed personal area networks and simultaneously providing location information. Also flexible communication schemes would allow downlink capabilities and transfer of information to personal area networks (individual workers/machines) from the upper level system. The zonal location scheme works flawlessly in underground conditions (as it was demonstrated during WP5 activities). This approach of location and tracking will be further researched with view to potential application for rescue action support in recently started RFCS project EMTECH.

3.5.2.5 Deliverables of WP2

The deliverables produced within WP2 are listed in Table 3.5.2-1 below.

Deliverable	Type	Task
Smart wireless sensors for temperature, humidity, pressure, rock-stress measurement and RFID tags	Prototype	T2.1
Alternative power supply units for smart sensors and devices	Prototype	T2.2
Interface connectors and electronic control units	Prototype	T2.3
Mobile and stationary RFID read and write equipment	Prototype	T2.4

Table 3.5.2-1: Deliverables produced within WP2

3.5.3 Development of applications for the utilisation of smart wireless sensor networks (Exploitation WP3)

3.5.3.1 Temperature monitoring in the area of conveyor belt drives with sensor networks (Task 3.1)

It is expected that from the developed prototypes the final revision will be derived. This would be only possible after further extensive field trials are carried out in real coal mine conditions. However, it is assumed the prototype sensors will be certified to ATEX in course of internal EMAG's activities related to future improvements of the SMP-NT type gas measurement and fire detection system (a product being currently in EMAG's portfolio). The final product consisting of the sensors and sink node can be incorporated into the mentioned system or will be able to work as standalone system being replacement to currently used bimetalic safety switches. Upgrade of the mentioned fire detection system by introduction of detection of pre-failure states rather than early fires will positively impact safety and economical factors related to maintenance.

3.5.3.2 Self-organising networks for advanced monitoring of the infrastructure in mines (Task 3.2)

Tests showed that the feature of self-organising meshed nets have essential advantages, since redundant linking between several possible communication lines improves the safety in utmost extent.

The ZigBee WSN has been exploited within the project by the other WP's and tasks for several applications. It is versatily usable for many applications. Within task 5.2 it was tested underground and the further exploitation activities are described there.

3.5.3.3 Monitoring Rock Stress (Task 3.3)

With the certified rock stress measuring system developed within this Task of the RAINOW-project, a possible pilot-application is already discussed and should be installed in summer 2009 in one of the German underground mines. The results of this task were also used within task 5.2, where the system was tested underground.

3.5.3.4 Development of an underground RFID-based navigation and tracking system for machines, material flow and persons (Task 3.4)

The solutions and results out of this task can be utilised and be further developed in the new RFCS-supported project EMTECH (RFCR-CT-2008-00003) started in July 2008. One essential Task of this project deals with tracking and localisation of work staff in the case of emergency situations.

Since the developed systems were tested within WP5, further exploitation intentions are described there.

3.5.3.5 Wireless Sensors Access with PDA's (Task 3.5)

The developed server/client software for use at the Iroc-PDA will be applied during installation and operation of the rock stress pilot project described as exploitation of task 3.3.

3.5.3.6 Gathering and Collation of Operational Data for All Wireless Devices (Task 3.6)

The results of the interference measurements within this task (especially carried out for underground concerns) are universal and can be used for every installation or extension of underground wireless transmission equipment. They were exploited within the project for underground testing within WP5 and will be further exploited along with all applications of WSN's mentioned as intended exploitations of the results of RAINOW (e.g. rock stress monitoring pilot application, see task 3.3).

3.5.3.7 Deliverables of WP3

The deliverables produced within WP3 are listed in Table 3.5.3-1 below.

Deliverable	Type	Task
Smart sensor mine infrastructure network	Application	T3.2
Wireless rock stress monitoring	Application	T3.3
RFID-Tracking System	Application	T3.4
Mobile Device to communicate with WLAN-Sensors	Hardware/ Application	T3.5
Sampled information about operating the WLAN-Equipments	Report	T3.6

Table 3.5.3-1: Deliverables produced within WP3

3.5.4 Development of personal area networks for tracking, monitoring and guidance under health & safety aspects (Exploitation WP4)

3.5.4.1 Development of smart personnel sensors for health and safety values (Task 4.1)

Some Polish entities as CSRG and K.W.S.A. are interested in the use of the health monitoring system developed during the project. The primary application will be to monitor the physiological parameters of the rescue team members, so it is expected to introduce the developed device to the market as soon as the certificates are obtained.

3.5.4.2 Smart personal sensors for environmental values (Task 4.2)

Although at the moment some economical issues make the integration of the wireless environmental smart sensors into all the mining cap lamps difficult, some representatives of this kind of mining equipment manufacturers are interested in it. Corresponding conversations are being conducted.

In addition, practical evaluation of applicability of the sensor set for assessment of environmental conditions in safe havens and during the rescue operations is envisaged within RFC-PR-07016 project EMTECH (Mine Emergency Support Technologies).

The integration of environmental sensors measurement to the m-Comm system means an added value to it, making the product more attractive from the market point of view.

3.5.4.3 Integration of personnel voice communication (Task 4.3)

A prototype of headset including PAN connectivity was shown on 21st World Mining Expo and Congress in September 2008, having a positive feedback. It is expected to introduce the product into the market by means of Telvis Company.

The integration of digital voice devices with high speed communication systems (as the currently one under developing in NEMAEQ project, RFCR-CT-2006-00001, using also results of RAINOW), means a great improvement in the voice communication field in comparison with the current analog lines, allowing noiseless talks, more than one conversation simultaneously per line, etc.

3.5.4.4 Wireless adapting of mine rescue communication systems for hands-free operation (Task 4.4)

The introduced improvements to the m-Comm rescue communication system (already commercialised), made it more attractive from the marketing point of view, due to especially the introduction of wireless communication support. It means a significant step forward for the rescue personnel mobility, allowing them to keep continously in contact with the trunk voice line.

3.5.4.5 Development of a personal communication interface for WLAN access (Task 4.5)

Both the roadway amplifier with Bluetooth interface and the PAN-WLAN gateway devices are being certified by two notified bodies (LOM and OBAC) and they will be put on the market as soon as the certificates are obtained.

Regarding to the roadway, the Spanish mining company HUNOSA is interested in introducing this new design into their monitoring and control systems based on RELIA-2000. Currently first prototypes are being testing in their coal mines, expecting its commercialisation by June 2009.

3.5.4.6 Personnel tracking and guidance in critical situations (Task 4.6)

Currently, a new prototype of the portable location device developed in the project is being manufactured. Although it is capable of performing it, first prototypes of this device will not provide information to the user about its position or emergency situation warnings in order to make easier and faster this first stage of the product commercialization. Due to the smaller size of this new version of the design it can be integrated into the mining cap lamps.

The development of this new version is being performed together with a lamp cap manufacturer interested in incorporating the functionality offered by this devices into his products.

3.5.4.7 Deliverables of WP4

The deliverables produced within WP4 are listed in Table 3.5.4-1 below.

Deliverable	Type	Task
Prototypes of explosion proof, low power, sensors for physiological values	Prototype	T4.1
Prototypes of explosion proof, low power, sensors for environmental values	Prototype	T4.2
Digital voice communication device and software interfaces	Prototype	T4.3
Emergency-rescue communication system radio link	Prototype	T4.4
WLAN access devices	Prototype/ Software/Drivers	T4.5
Personnel Tracking and guidance system	Prototype	T4.6

Table 3.5.4-1: Deliverables produced within WP4

3.5.5 Operational trials programme in underground mines (Exploitation WP5)

3.5.5.1 Test-run, trials of Mines Rescue communications system in underground mines (Task 5.1)

The outcome of the RAINOW project research into underground propagation, investigation of wireless technology, and exploitable commercial products has culminated in successful advancement of mines rescue communications in the UK and potentially in Europe. There is now a fully tested wireless mines rescue apparatus with pending ATEX approval that will enable safer and more efficient rescue operation to take place. An ability to traverse kilometres into an underground mine fully self sufficient/contained with the ability to communicate with a fresh air base is paramount in the aftermath of emergency/incident.

The wireless m-Comm will be a new product option for RMT to be offered to the market and it is expected that mines rescue organisations will take advantage of these fully developed and tested safety related communications products. Since the wireless m-Comm will have ATEX approval it will also become available to the whole of the European mining community.

The RAINOW project also identified future wireless technologies better suited to mining applications and power conserving technologies that would greatly benefit intrinsically safe and portable equipment. Ultra Wide Bandwidth, UWB, wireless systems which are just beginning to emerge commercially, have been highlighted as the technology that will provide better coverage as well as automatically generating distance information in underground mine applications. The system has been designed to incorporate this technology when available. With regard to the problem of powering remote wireless systems it was realised that extremely low power electronics were one way forward. It is technically more feasible to reduce the power demand by a 100 than to increase a given battery's stored energy capacity a 100 times. Unfortunately, there were only limited products available to be exploited within the period of this project. More very low power products are now emerging that could be suitable for remote sensors, etc., where an internal battery would be fitted for life (assuming a life of less than 20 years).

The roadway amplifiers with wireless connectivity that were developed and tested can be installed into working areas with machinery, solving most of the current problems caused by the high noise levels. In addition, its installation assures the correct reception by the workers of warnings and alarms messages sent through the intercommunication voice system and allows information about the location of each portable device (and consequently the person who carries it) to be known. This would be very useful in the event of an emergency.

Currently the ATEX certification process of the roadway amplifier with Bluetooth connectivity has started. The certificate is expected by the end of 2008 and commercialisation will commence immediately after.

3.5.5.2 Installation and trials of Smart Sensor Networks (Task 5.2)

The wireless Chirp sensors, the I/O unit and the processing unit have then become series products (standard products) of the manufacturer company Rittal, Germany.

Now there is the possibility to introduce these sensors in mining industry underground. An ATEX certification has not yet been accomplished, but this is intended by DMT.

The wireless connectivity applied to the control and monitoring system could replace the traditional cable bundle (**Figure 3.5.5-1**). This not only translates into a cost saving in the heavy duty cable and connectors (normally quit high) but it also allows a reduction in electrical contact failures, especially when they are placed in a harsh environment with a high humidity degree (or even water) and large quantities of dust.

Another significant advantage is that the wireless nodes can be mounted onto/into mobile machinery, monitoring and controlling the parameters remotely in real time. An important benefit to mobile equipment is the localisation of the machine or personnel (described in Tasks T4.6 and T5.3). The designed devices are ready to be certified. First conversations with the mining industrie have been done and HUNOSA as a Spanish coal producer showed interest on this technology.

Figure 3.5.5-1: Group of cables (blue) for control and sensor elements connection

Results of the development work carried out in RAINOW project on ZigBee based wireless sensors and actuators are used in ongoing RFCS project NEMAEQ for implementation of wireless network for monitoring of longwall equipment. For that purpose wireless nodes based on already developed hardware, but with RF power amplifier option and based on latest revision of networking stack ZigBee Pro compliant, were developed.

EMAG also plans to commercialize the results after more extensive field trials with large scale network are performed and appropriate approvals are obtained. The wireless sensors and the gateway units will be further tested in larger scale permanent network configuration in course of ongoing EMAG’s EUREKA (project No 11.3943.7). Currently the developed devices are used for research purpose in multi-spot safety parameter acquisition. The large scale tests will be combined with trials of micro-

ZIST distributed data acquisition system in methane-free mine (copper mine Polkowice/Rudna is initially agreed to be the test site). Within the abovementioned EUREKA project ATEX certification procedure for the wireless sensors will also be performed.

One possible application for the active transponders (RFID) in mines underground is the tracking of material transport units (containers).

The technology allows a fully automated and continuous tracking of material transport units and is very advantageous compared with alternative technologies. The barcode label technology for example, still requires a person who scans the barcode with a barcode imager in connection with a pocket PC. Besides, only punctual tracking information is available. I.e. the location of a material container is known only for these times, when the barcode was manually scanned. A passive transponder technology would also allow fully automated continuous tracking like active transponders, but it requires two transponders per container, because the distance between transponder and antenna must be very short. Only one active transponder is necessary for that, because the range is much farther and it can detect and transmit information of the moving direction. For active transponders the antenna can be positioned very flexibly. A ‘gate’ can be built with it, which covers the whole cross-section. No matter where the transponder passes the ‘gate’, it will be surely detected.

The manufacturer of the developed RFID transponders intends to market the equipment internationally, both, for applications where an ATEX approval is not necessary (e.g. opencast mining, stuck pile access gate, freight transport, underground mineral mining) and for the underground coal mining market, where an ATEX approval is necessary. For the latter, the manufacturer, who was involved as subcontractor within RANOW, intends to design an ATEX approved model (explosion-proof equipment).

RAG is currently discussing with the manufacturer to protect the invention of the active transponders by a common utility patent. Possibly, as a next step the technology will be installed and used in an underground mine for demonstration and as reference in order to support its international marketing.

3.5.5.3 Installation and trials of Personal Area Networks (Task 5.3)

Information about personnel (location and status) can be provided by the coordinator to the SCADA through the fieldbus. A more sophisticated application, similar to the beta version developed for the trials, can be integrated in the SCADA. This integration should allow, for example, warning message to be sent automatically to the corresponding underground personnel when an alarm has been triggered within a specific area of the mine. In each case the best route is calculated and personal instructions for that person’s location are generated. Further development is needed to create route algorithms and graphical guidance tools as well as the integration into SCADA.

A novel solution for underground tracking of personnel, vehicles and mobile plant has been developed using ZigBee PRO ratified technology (EmberZNet). Using a standards-based approach would help ensure a prolonged product shelf-life of a commercialised product. This type of application is very relevant to the requirements of the current needs of the international mining community, particularly following the MINER (Mine Improvement and New Emergency Response) Act 2006, which was issued by the US Governments MSHA (Mine safety and health administration). The MINER Act was issued during the RAINOW project, and has specific requirements concerned with improved underground communications and tracking. Research results have been disseminated from the project, a paper was presented at the 32nd Safety in Mines Research Institute Conference in 2007.

The developed sensors for heart rate monitoring are targeted at personal health conditions monitoring during the rescue action. They can be used during day-to-day operations as well. There is a commercial interest of Polish mining related entities (i.e. CSRG and KWSA) in the final solution for the heart rate monitoring system. As soon as the ATEX approval is obtained the devices will be introduced to the market. The ATEX certification will be carried out after the miniature sensor hub in a form of a wrist watch with a few customer oriented features required by CSRG is ready (this work is currently pending). With regard to other areas of dissemination it is envisaged that the developed sensors for health and environmental parameters will be also used for purpose of RFCS project EMTECH ‘Emergency Support Technologies’.

3.5.5.4 Deliverables of WP5

The deliverables produced within WP5 are listed in Table 3.5.5-1 below.

Deliverable	Type	Task
Underground trials of Mines Rescue Systems	Report	T5.1
Underground trials of Sensor Networks	Report	T5.2
Underground trials of Personal Area Networks	Report	T5.3

Table 3.5.5-1: Deliverables produced within WP5

3.5.6 Overview of results and their exploitation

N°	Result	Type	WP/ task refe-rence	Description	IPP[3]	Exploitation[3]
1	ZigBee sensors	D	2.1	Prototype sensors	PI[4]	Larger scale tests in semi-permanent network, further optmistion and ATEX certification within project 11.3943.7 of EUREKA[4] Publication in MIAG journal No 5/2008[4] Internal Seminar[4] Used for fire detection system (see result n° 8) Further development in NEMAEQ, MINTOS and EMTECH[4] The design is copyrighted[4], and its embedded control software is hardware copy-protected[4]
2	Chirp sensors	D	2.1	Prototype sensors and base station	NE[†]	Commercialisation[10] Certification for rock stress monitoring[3] Used for rock stress monitoring (see result n°10) NE[†] several used components are already protected by the component producers
3	Energy harvester	D	2.2	Prototype energy harvester converting vibrations into electricity	NE	Exploitable for future projects (further technological progress necessary)[3]
4	Data acquisition gateway	D	2.3	DAG-1 interconnects wireless LAN, FO backbone and multiple interfaces	NE[†]	Used for rock stress monitoring (see result n°10) Use to expand distributed wireless networks: A matching application within an online condition monitoring system is currently projected for German mine 'BW-West'[3, 1] NE[†] several used components are already protected by the component producers

[3] Number refers to company or institution in appendix A

N°	Result	Type	WP/ task refe- rence	Description	IPP[3]	Exploitation[3]
5	Interfaces for ZigBee WSN	D	2.3	Prototype interfaces for Zigbee WSN (to RS485 and V.34 modem)	PI[2, 4]	Market introduction[2,23] Certification[2] Larger scale tests in semi-permanent network, further optimisation and ATEX certification within project 11.3943.7 of EUREKA[4] Upgraded to power amplified revision in NEMAEQ[4] For some devices the design is copyrighted[4], and its embedded control software is hardware copy-protected[4]
6	Active RFID equipment	D	2.4	Active dual-band RFID system (transponders, stationary and mobile read/wite equipment, software)	PI[1, 38]	Market introduction[38] Certification[38] Underground demonstration[1, 38] Common utility patent[1. 38]
7	Zonal location software	S	2.4	Software for zonal location system based on RFID employing LR-WPAN networks	NE†	Use at exploitation of result n° 11 Further development in EMTECH and EMIMSAR[5] †IPP Not intended as software is protected under copyright law
8	Fire detection system	AS	3.1	Prototype of new reliable early fire detection system for belt drives, based on WSN	PI[4]	Field trials in EDAFIC[4] Commercialisation[4] The design is copyrighted[4], and its embedded control software is hardware copy-protected[4]
9	Software for higher process level applications	S	3.2	The software for self-organising meshed nets, which can be easily integrated within existing mining communication infrastructure	NE†	Used for Smart Sensor Trails in WP5[5] †IPP Not intended as software is protected under copyright law
10	Rock stress monitoring system	AS	3.3	Online measuring system based on WSN, superseding previous extensive wiring.	NE†	First operational application planned for summer 2009[1, 3] NE† Application of results n° 2 and 4
11	RFID tracking system	AS	3.4	Wireless sensor networks suitable for navigation and tracking of personnel and material in defferent environments of data transmission infrastructures.	NE†	Further development in EMTECH and EMIMSAR[5] Examination of RFID led to the WSN based prototype in WP4[5] (see result n° 18) Tests using WLAN system[1, 3] NE† Application of results n° 6 and 7
12	Wireless sensors access with PDA	S	3.5	Software to enable a PDA to access WSN data locally underground.	NE†	Use and exploitation in connection with result n° 10 NE† Extension of functionality of an existing PDA

N°	Result	Type	WP/ task refe- rence	Description	IPP[3]	Exploitation[3]
13	Health monitoring system	AS	4.1	Health monitoring system aimed for underground applications personnel.	PI[4]	Certification and market introduction after further development in EMTECH[4] (it is intended to introduce also rescue operation specific functionality to the final product) The design is copyrighted[4], and its embedded control software is hardware copy-protected[4]
14	Environmental monitoring system	AS	4.2	Multi-sensor node including advanced features	PI[4]	Similarly as at result 13 this design will be integrated with the cap lamp VLF and VHF location beaconing which is being developed in EMTECH project.[4] The design is copyrighted[4], and its embedded control software is hardware copy-protected[4]
15	PAN headset	AS	4.3	Mining headset including PAN connectivity.	PI[4]	Market introduction and certification[17] The design is copyrighted[4], and its embedded control software is hardware copy-protected[4]
16	Wireless m-Comm	AS	4.4	m-Comm rescue communication system with a) Bluetooth wireless support b) elimination of manual squelch control c) Potential for physiological monitoring	NE[†]	Previous m-Comm system upgraded using available technology. [6] [†]Original IP already published. [6] ATEX certification pending[6] Will be actively marketed as soon as certification granted[6]
17	WLAN access devices	AS	4.5	Roadway amplifier with Bluetooth interface and PAN-WLAN gateway devices	PI[2]	Certification[2] Integration into existing monitoring systems and commercialisation[23]
18	Personal tracking and guiding system	AS	4.6	Prototype personnel location tracking system	PI[2, 24]	Manufacture of new prototype.[2] Integration into mining cap lamps[24] Used for Personal Area Network Trails in WP5[5] Further development in EMIMSAR[5]
19	Knowledge on propagation of GHz EM waves in mines	IR	1.1	New knowledge resulted from basic research.	NE	Exploited within the project. Exploitable for other projects involving underground radio communications and data transmission.
20	Knowledge on underground applicability of different wireless standards	IR	1.2	New knowledge resulted from basic research.	NE	Exploited within the project. Exploitable for other projects involving underground radio communications and data transmission (e.g. NEMAEQ[6]).
21	Market analysis of WSN	A	1.3	Tabular market analysis of WSN. Status of March 2006	NE	Exploited within the project. Not exploitable for others anymore, because outdated due to rapidly evolving technology.

N°	Result	Type	WP/ task refe-rence	Description	IPP[3]	Exploitation[3]
22	Layout criteria for smart WSN	IR	1.4	Specification, knowledge on interference between Bluetooth, Zigbee and WiFi, technical review of Compact and Microstrip Antenna Technologies.	NE	Exploited within the project. Exploitable for other projects involving underground radio communications and data transmission (e.g. NEMAEQ[6]).
23	Alternative Power Supply Strategies for WSN	IR	1.5	Technology review and evaluation resulted from basic research.	NE	Exploited within the project. Exploitable for other projects (after update due to rapidly evolving technology).
24	Operating systems for WSN	IR	1.6	Characteristics of different operating systems and appraisal of their suitability for different WSN applications	NE	Exploited within the project. Not directly exploitable for others, because specific to needs of RAINOW.
25	Operational data of WSN	IR	3.6	Operational data of the wireless devices, particularly about interference at underground use.	NE	Exploited within the project. Will be used at the exploitation of the WSN applications.

Table 3.5.6-1: Overview of results and their exploitation

Legend

Type of result:

D= Device, IR= Internal Report, PR= included in Publishable Report, A= Analysis, S= Software, AS= Application System

IPP (= Intellectual Property Protection):

NE= Not eligible for IPP (e.g. because of basic research), PR= Protection/patent registered, PP= Protection/patent pending, PI= Protection/patent intended,

4 GLOSSARY

4.1 ABBREVIATIONS

ADC	Analogue to digital converter
ANSI/AMIEE	American National Standards Institute
ASIC	Circuit Integrated for Specific Applications
ATEX	ATmosphere EXplosible (Series of EC Directives related with explosive atmospheres)
Bluetooth	Ad-hoc wireless networking standard
bps	bits per second
CGI	Common Gateway Interface
Chirp	Type of signal modulation
COM	Windows serial port
CSR	Corporate Social Responsibility
CSS	Chirp Spread Spectrum
CTCSS	Continuous Tone Controlled Squelch System
CW	Continuous Wave
DAG	Data Acquisition Gateway
DMEC	Dynamic Movement Energy Converter
DSP	Digital Signal Processor / Processing
ECG	Electrocardiogram
EDAFIC	An RFCS project
EmberNet	Proprietary wireless mesh network standard
EmberZNet	ZigBee ratified wireless mesh network standard
EM	Electro-Magnetic
EMI	Electro-Magnetic Interference
EMIMSAR	An RFCS project
EMTECH	An RFCS project
EUREKA	An European research programme
FCC	Federal Communications Commission
FO	Fiber Optic
FTP	File Transfer Protocol
GUI	Graphical User Interface
GW	Gateway
HW	Hardware
HTTP	Hypertext Transfer Protocol
IC	Integrated Circuit
IEEE	Institute of Electric and Electronic Engineers
ISM	Industrial, Scientific and Medical (band)
LF rx	Low Frequency band receive
LOS	Line Of Sight
LQI	Link Quality Indicator
LR-WPAN	Low Rate Wireless Personnel Area Network
MED	Mobile End Device

MINTOS	An RFCS project
MySQL	Open source implementation of SQL (see SQL definition)
NEMAEQ	An RFCS project
NiMH	Nickel-metal hydride battery
PAN	Personal Area Network
PCB	Printed Circuit Board
PDA	Personal Digital Assistant
PER	Packet Error Rate
PHP	Personal Home Page (Tools)
PRT	Platinum resistance thermometer
PTT	Push-To-Talk
QRS	Wave with the three vectors Q, R, S
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SCADA	Supervisory Control And Data Acquisition
SMD	Surface Mount Devices
SMP-NT	‘System Metanowo Pożarowy’ (Methane measurement and fire detection system) a product of EMAG
SoC	System on Chip
SQL database	Structured Query Language
TBW	Trainingsbergwerk (training mine/ test mine in Recklinghausen, Germany)
TCP/IP	Transmission Control Protocol/Internet Protocol
UCR	Unidad de Control RELIA, RELIA Control Unit
UCR-WIZ	New RELIA Control Unit with wireless connectivity
USB	Universal Serial Bus
UWB	Ultra Wide Band
VHF tx	Very High Frequency band transmission
WiFi	WLAN to IEEE 803.11.x standard
WLAN	Wireless Local Area Network
WP	Workpackage
WSN	Wireless Sensor Network
ZigBee	A Wireless Sensor Network Standard, built on the physical layer and medium access control defined in IEEE 803.15.4 Standard
ZR	ZigBee Router
ZIST	Zintegrowany Iskrobezpieczny System Transmisji: (transl. integrated intrinsically safe transmission system) – produced by EMAG

5 List of Figures and Tables

5.1 List of Figures

5.2 LIST OF TABLES

5.3 LIST OF REFERENCES

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6 Appendix - Companies/ Institutions Referred to in this Report

N°	Company	Address	Telephone / Fax	Web
1	RAG Aktiengesellschaft	Shamrockring 1, DE-44623 Herne Germany	+49 2323 15-3075 +49 232 15-153627	www.rag.de
2	AITEMIN	Margarita Salas, 14, Parque Leganés Tecnológico, ES-28918, Leganés (Madrid), Spain	+34 91 442 49 55 (+34) 91 441 78 56	www.aitemin.es
3	DMT GmbH & Co. KG	Am Technologiepark 1, DE-45307, Essen, Germany	+49 201 172-1744 +49 201 172-1942	www.dmt.de
4	EMAG	Leopolda 31, PL-40189, Katowice, Poland	+48 32 2007-835 +48 32 2007-701	www.emag.pl
5	MRSL	Leeming Lane South, Mansfield Woodhouse, Mansfield, Notts., NG19 9AQ. UK	+44 13 26 37 18 76 +44 1623 427257	www.minesrescue.com/
6	Golder Associates (UK) Ltd (trading as Golder RMT) [former Rock Mechanics Technology Ltd (RMT)]	Bretby Business Park, Ashby Road, Bretby, Burton-on-Trent, Staffordshire DE15 0QD UK	+44 1283 522 201 +44 1283 522 279	www.golder.com
7	Texas Instruments:			http://www.ti.com
8	Ethernut: egnite GmbH	Erinstr. 9 44575 Castrop-Rauxel Germany	+49 2305 441 256 +49 2305 441 487	http://www.ethernut.de
9	Chwalowice mine:	KWK"Chwałowice" 44-206 Rybnik ul. 1 Maja 26		
10	Rittal GmbH & Co. KG	Auf dem Stützelberg D-35745 Herborn	+49 2772 - 505 - 0 +49 2772 - 505 - 2319	http://www.rittal.de
11	BlueRadios	7173 S. Havana Street, Suite 600 Englewood, Colorado 80112. USA.	303-957-1003 303.845.7134	http://www.blueradios.com sales@BlueRadios.com
12	Fundación Santa Bárbara	Escuela Laboral de Laciana, en Caboalles de Arriba (León). Spain.	+34 987 52 30 69 303-957-1003	http://www.fsbarbara.com fsb@fsbarbara.com
13	Zabytkowa Kopalnia Węgla Kamiennego GUIDO	ZKWK Guido ul. 3 Maja 93 41-800 Zabrze Poland	+48 32 714077	http://kopalniaguido.pl
14	CSRG – 'Centralna Stacja Ratownictwa Gorniczego' (tr. central mines rescue station)	ul. Chorzowska 25 41-902 Bytom Poland	+48 32 3880 520	http://www.csrg.bytom.pl

N°	Company	Address	Telephone / Fax	Web
15	K.W.S.A. – 'Kompania Weglowa S.A.' (largest Polish coal producer)	ul.Powstańców 30 40-039 Katowice Poland	+48 32 757 22 11, 	http://www.kwsa.pl
16	ITAM – 'Instytut Technologiii i Aparatury Medycznej'	ul. Roosevelta 118 41-800 Zabrze Poland	+48 32 271-60-13 	http://www.itam.zabrze.pl
17	TELVIS Przedsiębiorstwo uslugowo produkcyjne Sp.z.o.o	ul. Karoliny 4 40-186 Katowice Poland	(+48 32) 203 08 28 	www.telvis.com.pl
18	OBAC Ośrodek Badań, Atestacji i Certyfikacji Sp. z o.o.	ul. Jasna 31, 44-122 Gliwice Poland	(+48 32) 39448294 	http://www.obac.com.pl
19	ITAM Zabrze.	Roosevelt'a 118 41-800 Zabrze Poland	(+48 32) 271-60-13 (+48 32) 276-56-08	http://www.itam.zabrze.pl
20	Time Domain Inc.	Cummings Research Park 330 Wynn Drive Suite 300 Huntsville, AL 35805	1.256.922.9229 1.256.922.0387	http://www.timedomain.com/
21	CML Microcircuits	Oval Park, Langford, Maldon, Essex, CM9 6WG, England.	+ 44 1621 875500 + 44 1621 875600	http://www.cmlmicro.com/
22	LOM	Alenza, 1 28003-Madrid (España)	913367009 914419933	
23	HUNOSA	Avenida de Galicia, 44.- 33005- Oviedo (España)	(+34) 985 107 300 	http://www.hunosa.es
24	ADARO	Parque Científico Tecnológico – Calle Luis Moya Blanco,82 – Edificio Adaro – 33203 Gijón – Asturias – España	+34 985 34 78 06 +34 985 35 83 78	http://www.adaro.es/
25	Free2move	30 Waterside Plaza New York NY10010 USA	+1 212 683 5552 +1 212 532 6173	http://www.free2move.se
26	Microchip	Corporate Headquarters Microchip Technology Inc. 2355 West Chandler Blvd. Chandler, Arizona, USA 85224-6199	(480) 792-7200 	http://www.microchip.com
27	Honeywell	Honeywell International Inc. 101 Columbia Road Morristown, NJ 07962 Phone: (973) 455-2000 Fax: (973) 455-4807	1-800-328-5111 	http://www.honeywell.com

N°	Company	Address	Telephone / Fax	Web
28	Analog Devices	Analog Devices Corporate Headquarters One Technology Way P. O. Box 9106 Norwood, MA 02062-9106	(781) 329-4700 / 1-800-262-5643	http://www.analog.com/
29	Telegesis	Marlow Business Centre 84 Station Road Marlow Bucks SL7 1NX United Kingdom	+44 (0) 1628 894347 +44 (0) 1628 894333	http://www.telegesis.com/
30	Equivital	Stable Block at The Grange 20 Market Street Swavesey Cambridge CB4 5QG UK	+44 (0) 1954 233430 +44 (0) 1954 233431	http://www.equivital.co.uk
31	Hidalgo Ltd	Stable Block at The Grange 20 Market Street Swavesey Cambridge CB4 5QG	+44 (0) 1954 233430	http://www.wideband.plus.com
32	BlueRadios	7173 S. Havana Street, Suite 600 Englewood, Colorado 80112. USA.	303-957-1003 303.845.7134	http://www.blueradios.com sales@BlueRadios.com
33	Fundación Santa Bárbara	Escuela Laboral de Laciana, en Caboalles de Arriba (León). Spain.	+34 987 52 30 69 303-957-1003	http://www.fsbarbara.com fsb@fsbarbara.com
34	Zabytkowa Kopalnia Węgla Kamiennego GUIDO	ZKWK Guido ul. 3 Maja 93 41-800 Zabrze Poland	+48 32 714077	http://kopalniaguido.pl
35	CSRG – 'Centralna Stacja Ratownictwa Gorniczego' (tr. central mines rescue station)	ul. Chorzowska 25 41-902 Bytom Poland	+48 32 3880 520	http://www.csrg.bytom.pl
36	K.W.S.A. – 'Kompania Weglowa S.A.' (largest Polish coal producer)	ul.Powstańców 30 40-039 Katowice Poland	+48 32 757 22 11,	http://www.kwsa.pl
37	ITAM – 'Instytut Technologiii i Aparatury Medycznej'	ul. Roosevelta 118 41-800 Zabrze Poland	+48 32 271-60-13	http://www.itam.zabrze.pl
38	Selectronic Funk- und Sicherheitstechnik GmbH	Panroder Str. 48 65510 Hünstetten (OT Strinz-Trinitatis), Germany	+49 - 6126 93 28-0 +49 - 6126 85 12	www.selectronic-funk.de/

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