

# Safety positioning for first responders to fires in underground constructions:

A pre-study of demands and possibilities

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## Abstract

This report presents the results of the SafePos pre-study, in which different technologies for safety positioning to be used by first responders were identified, and techniques for ad hoc positioning were evaluated. The aim of the project, was to test various systems for localisation and communication and narrow- and wide-band radio transmission techniques, and to further investigate how the presence of such a system could support fire and rescue operations in complex underground environments. Tests have been carried out in real, pre-existing mining environments, and complex office corridors with similar conditions to those of a mine as regards curves and obstructions have been used for introductory tests. A computer application for digital simulation has been developed and adapted to the system, although this only operates on a relatively basic level, so as to support the testing of the positioning and communication systems; thus, more can be done to improve performance for real-life applications. The analysis was conducted by studying the results of the experiments and linking them to expected usage during a fire and rescue operation. Tests have also been carried out in cooperation with the fire and rescue services in order to identify equipment and wearable technologies that could support and make fire and rescue operations in mines and other complex underground constructions safer and more efficient. In order to transfer information to and from these wearable technologies and to improve the likelihood of a safe and efficient fire and rescue operation, positioning and connectivity are requirements.

Keywords: Underground constructions, mine, fire safety, positioning, connectivity

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## Preface

This pre-study report contains the results of the SafePos – Safety Positioning for the Mining Industry – project, a co-operative study that is being undertaken by SP Fire Research and SICS (the Swedish Institute of Computer Science). The project is being performed within the Strategic Innovation Programme for the Swedish Mining and Metal Producing Industry (STRIM). The project focuses primarily on the challenge of positioning within the mining industry, but will also be of benefit in other complex underground facilities with long response routes. A reference group, consisting of representatives from both the mining industry and manufacturing companies, as well as the fire and rescue services, has followed the progress of the project.

The authors would especially like to thank Thomas Askemur of Björka Mineral, a member of the Omya group, for his allowing RF measurements to take place in abandoned parts of the mine; fire protection engineer Per Rohlén, for valuable photos and interesting discussions; Krister Palmkvist of the Södra Älvsborg Fire and Rescue Services (SÄRF), for providing expertise on BA firefighting and fire and rescue requirements; and Hans Höglén of Dräger, for lending the project oxygen BA equipment for the tests. The authors would like to direct a special thanks to the firefighters of the Mälardalen Fire and Rescue Department (MBR) for their involvement in tests and discussions, and the Greater Stockholm Fire Brigade (SSBF) for taking part in the interviews.

The authors would also like to address their thanks to Peter Burman at Boliden's Kristineberg mine, for his help with arranging the measurements and for guiding around the mine, and LocuSense AB, for supplying the SPIDA smart antennas.

From the reference group in particular, Mikael Nyström of Mobilaris AB and Erik Lundström of Penny AB have contributed to the final report with valuable and much-appreciated information.

## Summary

The aim of the project (a pre-study) was to test systems for localisation and communication and narrow- and wide-band radio transmission techniques, and to further investigate how the presence of such a system could support fire and rescue operations in complex underground environments. Tests have been carried out in real, pre-existing mining environments, and complex office corridors with similar conditions to those of a mine as regards curves and obstructions have been used for introductory tests. Tests have also been carried out in collaboration with the fire and rescue services in order to identify equipment and wearable technologies that could support and make fire and rescue operations in mines and other complex underground constructions safer and more efficient. A computer application for digital simulation has been developed and adapted to the system, although this only operates on a relatively basic level, so as to support the testing of the positioning and communication systems; thus, more can be done to improve performance for real-life applications. The analysis was conducted by studying the results of the experiments and linking them to expected usage during a fire and rescue operation.

The investigated narrow-band system that was initially expected to provide direction and positioning was not capable of the speed required to support further development for this project. The use in this respect is as part of an ad hoc system, represented by electronic pucks that are placed along the response route so as to provide a connection to the Incident Commander, or to back-up already-installed systems in case of system failures. The tests and interviews regarding required and preferable performance have provided useful information for research and development that can be used in the future. Due to the narrow-band system's inability to meet the required positioning performance and a failure to achieve the desired results regarding the possibility of improving positioning with narrow-band systems, an evaluation of wide-band techniques (ultra-wide band, UWB) was carried out. UWB has great potential with regard to both positioning and simultaneous connectivity – improving the possibilities for communication and information exchange during a fire and rescue operation. These introductory tests showed the potential to both provide positioning and improve connectivity in order to deal with the winding tunnels of a mine. Maintaining audio contact with the command and control centre through the BA (breathing apparatus) commander is a necessity in any fire and rescue operation. Improved information exchange beyond basic communication requirements is also a necessity in order to make an operation safer and more efficient.

# 1 Introduction

In recent years, a number of severe fires have occurred in Swedish mines. The severity of these fires has varied, but all clearly show the potential of such incidents to threaten the safety of both miners underground and the fire and rescue personnel performing a rescue operation. Examples of such fires include that of a portable compressor in Boliden's Kristineberg mine on 25 August 2013 [1], a vehicle fire in LKAB's Kiruna mine on 24 June 2014 [2], and the recent container fire in Boliden's Garpenberg mine on 3 March 2015 [3]. All of these fires represent not just single incidents in which mining personnel were put at risk, but also a halt in production that caused economic damage to the mining industry. Depending on the size of the establishment, the loss of production due to a severe fire can be up to 15 million SEK [4] per day of standstill.

Fire and rescue operations in underground constructions represent a great challenge for first responders, irrespective of whether they are a part of the mine's own organisation or of a municipal fire and rescue service. A mine with sub-drifts, levels, and dead-ends many hundred metres below ground is a complex environment, with long response routes for the first responders. Swedish mines have extensive obligations for preparedness and equipment according to Chapter 2 Section 4 of the Swedish Civil Protection Act (2003:778). This obligation in practice means that, in case of a fire, an organisation must have safety professionals or, in many cases, its own fire and rescue organisation. Such professionals are trained to use BA equipment and guide fire and rescue services within the complex environment, but are usually not involved in the actual fire and rescue operation itself. The recent fire incidents discussed above clearly show the importance of three main factors for a successful rescue operation:

- 1) Knowing where people are
- 2) Knowing where the risks are (in mines, these are usually vehicles)
- 3) Knowing how to reach the location (position of the fire, orientation)

Interviews performed with municipal fire and rescue services after the latest incidents suggest that a BA operation would have been utterly impossible to perform without the assistance of the guide from the mining industry [5]. Of course, other important parameters, such as the location of the fire, the fire's development, and available resources also affect the outcome of the accident, but the knowledge and information mentioned above always facilitate optimal decision-making and the work of the fire and rescue operation itself. To be able to manage the three issues outlined above, good communication is essential; in mines, however, as in large buildings with concrete reinforcement, communication can be interrupted, or even impossible. The concrete lining of some mine shafts can contain 40 kg of steel fibres per cubic metre, and the effects of this on the reflection/refraction of RF (Radio Frequency) transmissions and localisation algorithms are currently unclear and must be evaluated. It is important to learn the limitations of such positioning systems in this type of environment, and the only way of achieving this is by installing systems and testing them in real-time in realistic environments.

Positioning and communication during accidents and fires are of great importance in order to ensure safety and optimise fire and rescue operations. The research, development, and implementation of innovative technologies for safer fire and rescue operations has relevance to individual firefighters and mining staff, as well as to the broader mining industry. To provide safe, attractive, and equal working environments for men and women, contingency planning and possibilities for safe evacuation, with or without assistance from fire and rescue services, are needed. As interruptions to



production incur large costs. Therefore effective evacuation, as well as effective fire and rescue operations, are high priorities.

Fire and rescue operations can be divided into two main parts – assisting evacuation (rescue) and extinguishing the fire (firefighting). With limited resources, life-saving activities – i.e. saving persons trapped by fire – will always be the highest priority. With the advent of technologies to provide reliable and relevant information regarding the location of mine workers, as well as the fire and other risks in the immediate surroundings, the strategies and tactics of fire and rescue operations should be focused on the best solution as regards both the mine workers' safety and the minimising of standstill time. The possibilities afforded by being able to determine the position of BA firefighters with a high degree of precision not only provide improved safety for the individual, but also improvements to and optimisation of the fire and rescue operation as a whole.

This pre-study report details state of the art developments, and accompanying background information on fires in mines, as well as fire and rescue operations in underground constructions. Different areas are discussed and explored, with subsequent research in mind. Different technologies and the usefulness of various systems are explored and put into context with regard to their use in fire and rescue operations in mines. User needs and new technologies, which may be possible to use in an advanced future system for positioning and connectivity, are investigated with respect to the demands of future research.

## **1.1 Aims**

The primary aim of the project was to investigate and evaluate state-of-the-art technology for positioning in underground mines. Positioning is used in order to facilitate the localisation of persons in danger and vehicles that are located in mines. A secondary aim was to improve and contribute to first responder safety and efficiency by investigating ways of monitoring e.g. the location, air supply, and body temperature of BA firefighters. With improved abilities to find persons in danger, monitor BA firefighters, and exchange strategic information during a fire and rescue operation, fewer people will be harmed, the negative impact on the environment will be lower, and economic losses will be reduced. In addition, an improved knowledge of the whereabouts of transport or working vehicles may improve knowledge of risks related to potential fire spread or the location of the fire's origin. The project also aimed to contribute to safe and attractive working sites, to support regulations compatible with a growing industry, and to implement state-of-the-art technology for control along the value chain. The key factor in transferring and using this knowledge during real fire and rescue operations is to improve the accuracy of the positioning system, and to increase the possibilities for information exchange between the scene, the accident, and the Command and Control Centre.

## **1.2 Limitations**

The work does not refer to or suggest any developments regarding new products or guidelines. It only includes preliminary testing of some prototypes and a set of recommendations for future research and testing.

## 2 Background

Over the course of the last two decades, SP Fire Research has performed a number of research projects related to fires in underground constructions [6-12]. The main focus has been on fire development and fire and rescue operations in tunnels and other underground constructions. This knowledge and experience is world-leading, and has resulted in many journal papers, along with a PhD thesis by Rickard Hansen at Mälardalen University [14]. In addition, SP Fire Research recently published a book on tunnel fire dynamics [12] that has set an international standard for work in this field.

The main findings regarding the fields of positioning, communication, and information clearly show that additional research and development is needed, and that firefighting in complex underground environments needs to be supported by innovative technologies.

Development is particularly necessary with regard to better accuracy for localisation, more reliable sources for communication, and improved capabilities to transmit supporting data between BA firefighters and the Incident Commander. Additional information, such as BA firefighter monitoring, IR images from the scene of the fire, or two- or three-dimensional drawings as support for orientation, would further optimise fire and rescue operations and contribute to the safety of both miners and first responders.

### 3 Method

The work within this pre-study of the SafePos project has been performed across five different work packages (WP), which are presented below:

#### **WP1: Identification of products and technologies**

The first work package included a literature review and a seminar in which the research partners, mining industry, fire and rescue services, and the small- and medium-sized enterprises (SMEs) companies involved discussed the challenges associated with underground fire and rescue operations and the possibilities presented by innovative technologies to support such efforts. Both already existing and new technologies were identified and, based on the findings, the research group selected four different technology areas that were felt to be particularly capable of supporting a fire and rescue operation:

- Wearable technologies
- BA equipment and surveillance
- IR imaging
- Back-up systems related to connectivity and positioning

For each area, one or two technologies were chosen for further evaluation in WP2. The work in WP1 was led by SP Fire Research, but involved all project participants.

#### **WP2: Evaluation criteria and test preparations – fire and rescue**

In WP2, the identified technologies were further discussed with the mining companies and fire and rescue services. An evaluation of user needs was performed, and important parameters regarding user-friendliness in the context of mining environments were discussed. The equipment was evaluated with regard to feasibility in underground constructions and compatibility with fire and rescue services' standard equipment. Pre-tests of equipment prior to the feasibility tests were performed at the Fågelbacken<sup>2</sup> fire and rescue training facility. The feasibility tests were planned and the test site prepared in conjunction with those of the companies involved that manufacture fire and rescue equipment.

The technologies chosen for testing within the pre-study were wearable technology in the form of interactive information systems in BA masks, BA equipment with an oxygen supply, integrated IR imaging cameras, IR fixtures and lights, and sound and radio pucks related to the work in WP3. Some of the equipment, which was already in use or at higher TRLs (technology readiness levels), was tested under real conditions, while emerging technologies were discussed on a more theoretical level. The interviews were performed in a semi-structured manner with groups of 3-4 firefighters, with the interviewees allowed to talk without interruption provided they kept to the boundaries set out in the introduction. If they were not considered to have answered all of the questions required, the interviewer was instructed to obtain supplementary information. WP2 was performed by SP Fire Research.

#### **WP3: Test preparations, positioning, and communication – new technologies**

The purpose of this work package was to take the LocuSense SPIDA antennas from TRL

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<sup>2</sup> Fire and rescue training facility for MBR (Mälardalens brand- och räddningsförbund/Mälardalen Fire and Rescue Department) in Västerås, Sweden.

4 to TRL 5 in order to open them up for use in new applications. Within the frame of this work package, preparations for the feasibility tests in the Tistbrottet mine in Sala were made. The test results were evaluated, and decisions regarding complementary tests, as well as further testing with broad-band technology, were made. A second test series including both narrow- and broad-band techniques was planned and evaluated with respect to promptness and accuracy. This work package was conducted by SICS.

**WP4: Full-scale tests**

Feasibility tests were performed in Tistbrottet at the Björka mineral mine in Sala, where earlier full-scale fire tests of mining vehicles and methods for fire-fighting in underground constructions [11] had been performed. The test set-up included communication between nodes and the base station, and further testing of how the mining environment influenced communication performance between nodes. The tests were compared to earlier feasibility tests performed at Boliden's Kristineberg mine. WP4 was conducted by SICS, with support from SP Fire Research for the Tistbrottet tests.

**WP 5: Reporting and dissemination**

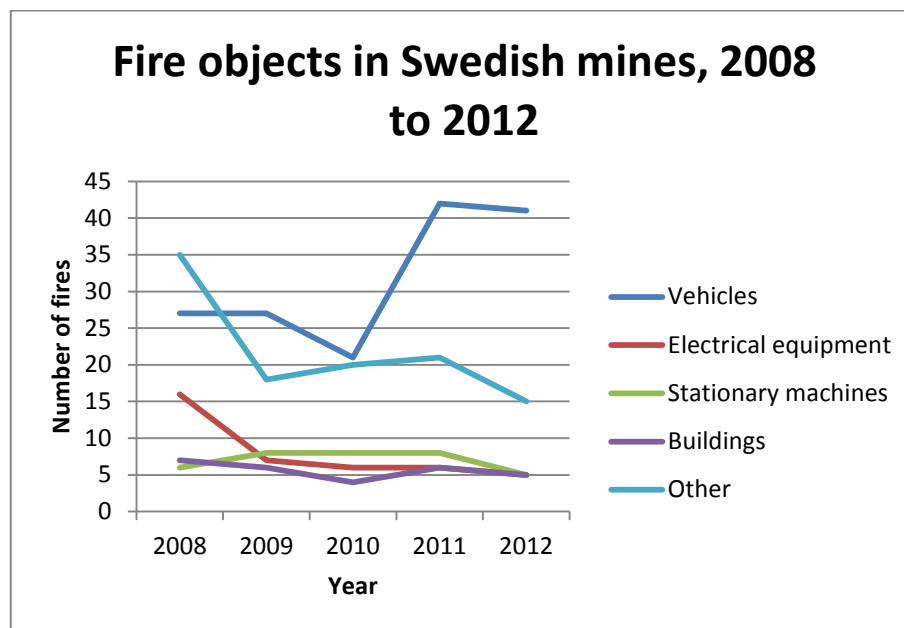
The results of the literature review, seminar, and feasibility tests are presented in this technical report in the SP Fire Research series. A kick-off workshop with stakeholders and project participants was held in September 2015 in Borås, the project was presented and discussed at the KCBU<sup>3</sup> open seminar and reference group meeting in Stockholm in November 2015, and in January 2016 a closing seminar was held in Stockholm in order to discuss the results with representatives from fire and rescue services. The report will be distributed to all project participants and reference group members in order to ensure full dissemination.

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<sup>3</sup> Kompetenscentrum för brandsäkerhet i undermarksanläggningar (KCBU) (the Swedish Centre of Excellence for Fire Safety in Underground Constructions).

## 4 Fires in underground constructions

Fires in hard rock mines relate mostly to vehicles. There are also storage units, workshops, garages, and staff facilities that represent underground fire loads and ignition sources. The burning behaviour of each of these different objects varies, and in most cases they are separated from one another and so there is a relatively small risk of fire spreading between them. The variation of each of these objects with regard to fire development and potential for spread of smoke to the rest of the mine is considerable. Vehicles are one of the main causes of fire, and the occurrence of fires in building components or stationary machines is considerably lower. In Figure 1, the fire object statistics for Swedish mines for 2008 to 2012 [13] are presented.



**Figure 1: The fire object statistics for Swedish mines for 2008 to 2012 [13].**

An underground mine can be distinguished by its maze of drifts, levels, ramps, shafts, etc., and it is not always possible to install fire barriers in all parts of a mine. Smoke evacuation may be limited in some areas and, in many tunnels or drifts, the path of the smoke may coincide with evacuation and response routes. Thus, the main risk to people in an underground mine during a fire is the spread of smoke, which results in poor visibility, smoke inhalation, and hampering of egress activities. The risk of being exposed to hot fire gases is relatively low in long tunnels.

### 4.1 Initial fires

Hansen [14] provides a concise summary of how vehicle fires in hard rock mines develop and spread. Vehicles are generally found in large numbers throughout a mine, and are not restricted to a certain number of places underground. As vehicles can be found in most parts of a mine and the likelihood of a vehicle fire must be accounted for, fire protection systems – foremost of which is the smoke ventilation system – are in many cases installed with the assumption in mind that a vehicle fire is the most plausible fire scenario. Fire hazards and fire load will vary from vehicle to vehicle depending on its characteristics, use, and dimensions. Common combustible components include diesel, hydraulic oil, motor oil, windscreen washer fluid, cables, hoses, interior (seats, dashboard, etc.) and

tyres. Large mining vehicles contain great quantities of diesel and hydraulic oil and possess tyres of large dimensions, and so a fully developed fire in such a vehicle often leads to rapid fire development, considerable smoke production, and a long-lasting fire. Figure 2, borrowed from Hansen, is a photograph of hydraulic hoses on the boom of a drilling rig that were tested as part of a large-scale test in Tistbrottet in 2010 [14].



**Figure 2: Hydraulic hoses on the boom of a drilling rig [14].**

As a result of the large number of mining vehicles, many tyres and hydraulic hoses are stored at facilities underground, as well as in general in workshops or the depots of contractors. The tyres found on larger mining vehicles, such as wheel loaders, are of considerable size and weight, adding several thousands of kilograms to the quantity of fuel stored at depots, workshops, and in the vehicles in question. Fires in tyres and, to some extent, in large quantities of hydraulic hoses are often distinguished by their considerable smoke production and long-lasting nature, which increase demands on egress safety in the mine [14].

All of these components can create a potential risk for fire development. In the next chapter, several shorter descriptions are given, based on the work performed by Hansen [14].

## 4.2 Fire development

Fire behaviour in a mine drift is highly dependent on the arrangement and distribution of adjacent combustible objects, the dimensions of the mine drift, ventilation conditions, and fresh air supply.

As the combustible materials are generally concentrated in certain locations, the likelihood of a fire spreading from the first location in which an item is ignited is generally small [14]. The few locations in an underground mine in which continuity in terms of fuel and high fire load can be found are office complexes, warehouses, and parking drifts or areas with several vehicles parked in close proximity to one another. These locations constitute the greatest risk for continuous fire spread. Outside of these, the distance to the nearest large accumulation of combustible items is considerable, and thus the risk of fire spread is lower. The height of the mine drifts is important, and in many cases is roughly 5-8 metres. In the event of a fire, the majority of hot fire gases are to be found in the upper region of the mine drift, where the quantity of combustible items is relatively few.

The drifts, levels, and ramps of an underground hard rock mine are characterised by their general openness, lack of barriers, sporadic pockets of combustible materials, and large distances of barren drifts in which the low temperature of the rock will cool off the smoke of the fire. The likelihood of a flashover is low in an open mine drift due to the wide distribution of combustible material and high heat loss due to rock. The same is true for levels or ramps, due to their openness and cooling atmosphere. Most important is the limited amount of combustible material (in terms of both quantity and spatial density) [14].

After the initial heating process, the rock in the area near to the fire increases the re-radiation mechanism and directs heat back to the fire, thus influencing the combustion process. The rock further downstream of the fire has more of a cooling effect on the fire smoke, and therefore decreases its stratification. The effect of the surrounding rock in terms of cooling will thus depend on its distance from the fire [14].

A fire occurring in a mine drift with a given longitudinal ventilation flow will behave differently than one in a mine drift with only one entry and limited air and, in the latter, a minor fire may eventually self-extinguish due to a lack of air from outside the fire site due to the inerting effects on combustion of the combustion products in the recirculated smoke [14].

As opposed to fires in enclosures, flames and fire plumes in a mine drift will be greatly affected by ventilation flow from a mechanical ventilation system, rather than natural ventilation alone, as is the case for enclosure fires. The effect on fire behaviour can be seen in e.g. the tilting of flames, which leads to faster flame spread and the ignition of adjacent fuel items. Besides tilting flames, ventilation flow also leads to an increased supply of air and oxygen to the fire site, increasing the mixing of oxygen and fuel and thus combustion efficiency. The large quantities of air available in mine drifts, due to their large dimensions, and the influence of mechanical ventilation make ventilation-controlled fires less likely to occur than e.g. enclosure fires. However, obstacles in a mine drift – such as equipment and vehicles – may block ventilation flow and reduce its influence on the fire plume and the possible tilting of flames. Additionally, the distance to the closest intake fan and intake shaft influences the amount of air flow available at the site of the fire, in that combustion efficiency decreases with greater distances. With longer distances and a decreased influence on the part of mechanical ventilation, a fire has a stronger influence on ventilation conditions and, above all, ventilation direction, possibly causing a reverse flow of fire gases into the ventilation airstream [14].

Fires in flammable liquids can be characterised by their fast growth, and their rapid and considerable smoke production pose a great threat to miners. A large number of mobile and stationary equipment requires flammable or combustible liquids such as diesel, hydraulic oil, motor oil, windscreen washer fluid, etc. Even though the use of flammable

or combustible liquids with lower flash points – such as petrol – is highly restricted or even forbidden, the hazardous practices of using and storing flammable or combustible liquids in an underground mine are nevertheless a factor that must be accounted for due to the distribution and quantities of such liquids [14].

### **4.3 The fire and rescue environment**

The greatest challenge faced by fire and rescue services is smoke. In mines, response routes are often long, and the drift can be filled with smoke. Movement within long, smoke-filled environments is very difficult. Unless a fire occurs within an enclosed space, such as a closed storage unit or office complex, the smoke from the fire will ascend and spread along the ventilation direction. The smoke spread in a mine drift is largely determined by the level of smoke stratification, which in turn is dependent on air velocity in the mine drift, the dimensions of the drift, the heat release rate, and the distance from the fire. With a low or non-existent forced air velocity, smoke stratification is high in the vicinity of the fire, while at the other end of the spectrum, at higher air velocities, smoke stratification is low downstream from the fire. With increasing mine drift height and distance from the fire, vertical temperature gradients decrease and, as a result, so does smoke stratification [14].

Another issue is so-called ‘backlayering’, i.e. smoke travelling in the opposite direction to that of the air ventilation flow. Backlayering usually occurs when the air ventilation velocity is low or moderate, depending on the heat release rate of the fire and the geometrical features of the mine drift. In the event of backlayering, hot smoke cools and descends towards the ground, diluting smoke travelling towards the fire source.. The backlayering phenomenon may hamper the efforts of fire and rescue personnel if the evacuation of refuge chambers is attempted during an ongoing and nearby fire [14].



## 5 The fire and rescue operation

The fire and rescue service in Sweden operates based on the Civil Protection Act (CPA) (2003:778; in Swedish, 'Lagen om skydd mot olyckor'). According to the CPA, all municipalities are required to have an appropriate organisation for fire and rescue services, which must intervene when an accident occurs or when the possibility of one occurring exists. The risks of intervention should always be considered and weighed against the possible losses – primarily lives – if an intervention is not performed.

There are no national rules regarding how the fire and rescue service will work in different scenarios. Many firefighters have comparable educations and backgrounds, and the similarities between different fire and rescue services are high. The capacities of an individual fire and rescue service, however, depend on the ability of the collective, based on the number of personnel and their education, training, and equipment. The regulations in the Work Environment Act (AFS 2007:7) for BA operations state that a BA operation should only be performed in the case of life-threatening events.

A firefighter must have access to a safe water supply<sup>4</sup> in order to safeguard their retreat route. Until recently, the prevailing interpretation of the regulation has been that it is not acceptable to enter mine drifts, even in low smoke concentrations and far away from the fire. However, recent conversations between the Swedish Work Environment Authority and the fire and rescue community indicate that intervention performed far away from a fire can be conducted without a water supply, provided other techniques are used to ensure that the risk of fire will not increase and thereby put the firefighters at risk. However, new technologies to support decision-making, improve surveillance, and safeguard firefighters need to be developed with regard to these scenarios and conditions.

### 5.1 The challenges posed by underground constructions

In underground constructions, without direct access from the outside to the scene of the fire, a fire and rescue intervention is more difficult. In deep mines the response routes are often very long. A BA operation in an underground construction is often the only option available for determining the extent of a fire. The focus in such an operation could be on assisting evacuation, extinguishing the fire, or a combination of the two [15]. Many previous fires and incidents [1, 2, 3] show that there is often a need for assistance so as to make evacuation possible. In deep mines with long response routes it can be difficult to follow the stipulations of the Work Environment Act, and still perform an effective fire and rescue operation. It is time-consuming to build up a water hose system with a safe water supply; for example, a 150 metre water supply can take between 15 and 30 minutes to construct [10]. If the fire is located many hundreds of metres from a safe and smoke-free location, a fire and rescue operation following a strict interpretation of the Work Environment Act cannot be performed. Another criterion that is repeatedly not met is the structure of the BA operation, as small vehicles are often used in mines to travel long distances. Real fire incidents and earlier research regarding fire and rescue operations for underground fires [8, 9, 10] clearly show the need for revised regulations and further research to support this work.

Due to the time-consuming nature of building up water supply system, Swedish BA operations can only penetrate 200 - 300 metres into a drift when using compressed air.

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<sup>4</sup> This entails BA firefighters bringing doubly-supported water hoses in order to safeguard their retreat route in case of fire.

Internationally, however, oxygen is often used for BA operations in mines and tunnels with long response routes. The greatest possible time-span for BA operations using compressed air is 30-40 minutes if large double bottles are used; for oxygen systems, this time rises to up to four hours.

There are, however, advantages and disadvantages to both system types. With compressed air systems it is possible to connect a BA colleague or a person in need of help to the air supply, which is not possible with a re-circulated oxygen system. Additionally, the use of compressed air has a cooling effect on the fire fighter due to the fact that the exhaled air leaves the system. Contrastingly, an oxygen system is closed, and the firefighter's air is re-circulated, cleaned, re-oxygenised, and re-used. Even if this air is cooled during the process, re-circulation causes the body temperature to rise, and so this is one of the limiting factors of oxygen systems. The choice of system determines which parameters are most important to monitor during a BA operation; air supply for compressed air systems, and body and air temperature for oxygen systems. Closed systems also limits the use of rescue air, as this needs to be supplied separately.

Even if the basic principles are similar for fighting fire above and below ground, underground fires represent far greater challenges. Firefighters have more practical experience working above ground, and there is often a need for more resources when fighting fires in underground constructions. The location and extent of a fire are important factors to know before resources are put in place. The possible locations in which a fire may have started and the ingress point for the rescue operation can be hundreds of metres apart, and so initial information to support the choice of response route is important. If firefighters access a site from the wrong location, it can be difficult to rearrange resources.

One of the largest challenges in fighting underground fires is obtaining relevant, up-to-date, and accurate information from the scene of the fire, such as smoke spread and the size of the fire. Situational awareness forms the basis for tactical and strategic decisions, but can be hampered by the complexity of the site of the accident. Long distances to the fire's origin can complicate rescue operations, and it can take an extended period of time for the fire crew to obtain a complete picture of the accident. For the Incident Commander, situational awareness is crucial to the outcome of the operation. In order to create a safe working environment for BA firefighters, it is crucial to know their locations and monitor their well-being [15].

## **5.2 Communication during a rescue operation**

During a BA operation, radio communication between BA firefighters and the BA commander, located in a safe place within or outside the underground construction, is essential for safety. Ensuring communication during BA operations is also a stipulation of AFS 2007:7, which states that it is not acceptable or possible to safely conduct a BA operation if the communication system is not functional. The problem in an underground construction, however, is that signals from a fire service's ordinary equipment are reduced to the extent that it is often impossible to use ordinary radio equipment. The concrete lining of some mine shafts can contain 40 kg of steel fibre per cubic metre. In practice, this means that RF transmissions are often interrupted or otherwise impaired due to reflection and refraction.

In addition to radio communication, it is preferable that BA commanders are aware of the position of firefighters during the entirety of the fire and rescue operation, and have access to important physical data such as air supply, body temperature, and heart rate, which can be monitored manually (via updates from the firefighters themselves) and

relayed to the commander. If this information could be monitored automatically, greater focus could be placed on other areas that could benefit the BA operation as a whole. IR images from the scene of the fire, transferred to the Command and Control Centre, could also facilitate decision-making throughout the fire and rescue operation.

### **5.2.1 The TETRA system**

The TETRA system was designed by the European Telecommunications Standards Institute (ETSI) for use by emergency services and government agencies for public safety networks and the like. The name of the TETRA-standard communication system used in Sweden is Rakel, a national digital communication network that is used by over 500 organisations, from the emergency services to the healthcare sector. Rakel is intended to collect all civil protection agencies together in one common forum, increasing information exchange across organisational and sector boundaries. 99.84% of Sweden's populated area and 95% of Sweden's total area are covered by Rakel. The system has its own infrastructure, with double connections throughout the network, and all base stations have backup power.

Group calling mode can connect a user to a selected call group with a single button push. Different call groups contain people or functions that need to co-operate in order to deal with specific issues during an incident. It is possible to listen to multiple call groups at the same time, as well as to temporarily create new ones when necessary. The communication is encrypted, and so it is possible to send confidential data.

In addition to group calling mode, the system supports individual calls between two people, and can also connect calls from an ordinary mobile network. Furthermore, it is possible to send an emergency call directly to a dispatcher, who can override any other activity taking place at the same time, supply information regarding positioning, send text messages, receive and send monitoring data, etc. Technical functions such as open ports and the monitoring of technical systems, e.g. electricity, water, and heating supplies, are also available through the system.

In emergency situations underground or in other areas with poor communication coverage, it is possible for rescue workers to maintain direct communication with one another using a series of TETRA terminals as relays [18]. An increasing number of fire and rescue services also use the Rakel system for communication during BA operations. The system performance in many underground constructions is, however, not yet fully developed, due to e.g. the fact that leaking cables need to be installed along the response route. The system does not at present support positioning with an accuracy sufficient for the usage discussed in this report.

## 6 First responder technology

Surveillance and information exchange are two of the most important parameters in ensuring a safe fire and rescue operation in a complex environment. The traditional mode of surveillance has long involved the manual monitoring of BA firefighters' whereabouts and air consumption. Interviews performed within the pre-study indicate that communication regarding this basic information can take focus away from the main task. The full-scale fire and rescue tests performed within the TMU project [10] also showed that information exchange was vital, but at the same time that it is deeply time-consuming. Automatic and reliable surveillance and information exchange would consequently make fire and rescue operations safer and more efficient.

### 6.1 Interviews with first responders

Interviews were performed on six different occasions, three of which involved personnel from Södra Älvsborg Fire and Rescue Services, two were conducted with personnel from Mälardalen Fire and Rescue Department, and one with personnel from Greater Stockholm Fire Brigade. The interviews, along with knowledge gained from earlier research projects [8, 9,10], showed that the potential improvements could be divided into four main areas:

- Wearable technologies (automatic surveillance of e.g. heart rate or body temperature)
- BA equipment for long-duration performance (with automatic surveillance of air supply)
- The integration of IR imaging technology in BA masks
- Improved wearability of BA masks (with wireless information transfer to the Command and Control Centre).

The interviews also included discussions of how equipment for improvised (ad hoc) positioning and connectivity networks should be designed in order to be user-friendly for first responders. What is meant by an 'ad hoc system' is one that is not pre-installed in the construction, but instead set up by the first responders during the fire and rescue operation. The discussed technologies were either directly connected to positioning or connectivity. Further technologies discussed depended on or were improved by the potential ability to transfer information between firefighters performing fire and rescue operations in underground constructions and the ground level or other relevant safe locations.

Over the course of the interviews and performed tests, the following viewpoints were stated:

- IR imaging should be displayed in the BA mask or attached to a wearable harness so that both hands are free during the fire and rescue operation.
- If IR imaging is displayed in the mask, which is preferable, it is important to maintain the ability to switch to normal sight if desired.
- Information displayed in the mask should not affect the adaption of firefighter's eyes to dark environments.
- It is desirable that the surveillance and monitoring of physical parameters and air supply functions without the need for audio contact.
- Warnings and information about personal air supply should be easily visible and accessible without use of hands. Existing telemetry systems should be adapted for use underground.
- Oxygen is considered to be suitable for use in incidents involving long response routes. It has been experienced that the double tubes from oxygen packs can

obscure vision and impede head movement to some degree. The largest problem experienced during the 45 minutes of testing was the BA mask losing visibility due to fogging on the inside of the mask.

- Positioning is considered to be an important safety parameter.
- If ad hoc positioning and connectivity systems are used, they should be lightweight, easy to place, and combined with illumination for visual improvement.
- Positioning and connectivity are considered to be important factors with regard to using remote-controlled vehicles or robots.

## 6.2 Augmented Reality technology

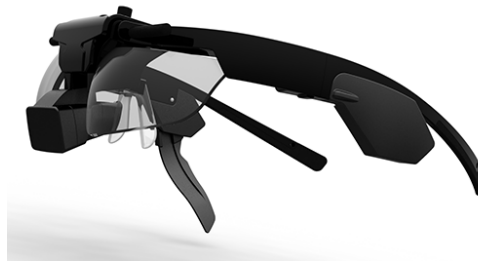
There are several new and interesting technologies related to the subject of BA operations that were deemed to be worthy of focus in this pre-study. Augmented Reality (AR) is used to superimpose a digital display over the user's visual field, and the information displayed can be used to support the performing of a task. In this text, AR will be explained from the perspective of a first responder. AR glasses as presented in this report use a positioning system. If the wearer is e.g. outdoors and above ground, this may take the form of a standard GPS system. By providing information regarding location, AR glasses can guide a user in moving from Point A to Point B and, by introducing a magnetometer, it is also possible to see which direction the user is facing. This is of importance if it is desirable to overlay graphics on top of reality for real-time guidance for specific actions which a user should perform, such as moving in a certain direction.

The AR glasses studied in this pre-study have transparent projection capabilities, head-motion tracking, jawbone-click sensing, and external sensor input. The latter could be used for e.g. IR imaging in smoke-filled environments. The selected AR glasses have been developed for military use, among other applications, but could with small modifications also be used by civil first responders to support fire and rescue operations in complex environments.

### 6.2.1 System description

The C Wear system consists of a spectacle frame and a computer box, connected by a HDMI cable. The computer box supports both Wi-Fi and Bluetooth 4. Like the other wearable technologies discussed in this chapter, connectivity is a basic requirement for the usage and positioning information needed during a fire and rescue operation. The chosen AR glasses do not have a built-in battery due to issues of ergonomics, and this is instead mounted on the computer box. For real-world use, the system would need to be adjusted and further developed so as to fit the BA mask used by firefighters.

The core technologies in the C Wear Interactive Glasses, as shown in Figure 3, are developed as individual modules, with the Spider Embedded System as the core unit.

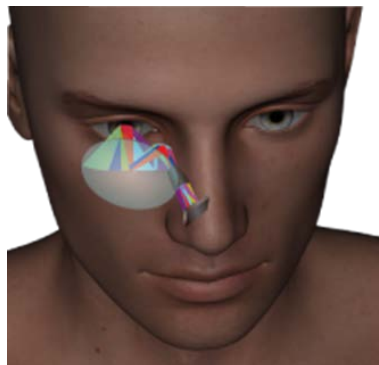


**Figure 3: C Wear Interactive Glasses from Penny AB.**

The glasses use an optical unit to project the image from the computer box directly onto the retina of the user's eye (see Figure 4). A motion-tracking system with a 3D MEMS Gyroscope is used to sense the head movements of the user, enabling navigation in the graphical user interface. The command button sensor is designed as a soft sensor and is mounted close to the user's masseter muscle, where it senses tension as the user moves their jaw, which allows the user to 'mouse click' on-screen. The external sensor system can, except for in IR applications, be used as part of other camera solutions for collecting information to be used as a basis for decision-making.

The optical unit in the glasses used in the pre-study is designed to give the user the following abilities, which have been judged to be valuable for applications in real-world environments:

- The graphics presented in the glasses are transparent, enabling the user to see both reality and the information provided.
- The Field of View (FOV) of the computer graphics in the optics cover one third of the eye's angle of vision: 40 degrees horizontally and 25 degrees vertically. This spread of graphical projection creates the equivalent of a 70" display, visible two metres in front of the user.
- The full-colour display sends the image through the optics and directly to the retina, with no backlight to blind the user when graphics are not shown on the display.



**Figure 4: The C Wear optical solution. Picture: Penny AB.**

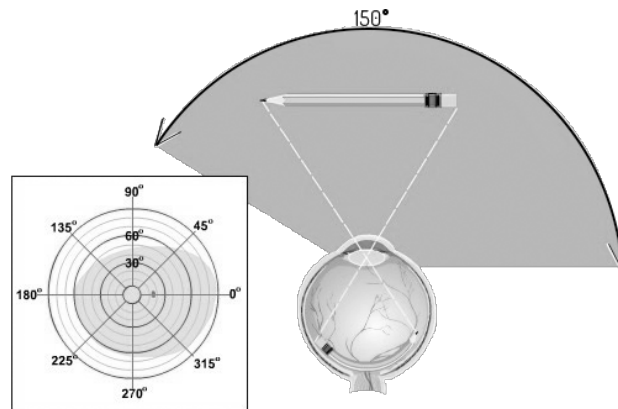
### **6.2.2 The eye and visual processing**

In order to discuss the ways in which the functionalities of AR may be implemented in an optical device to be used by first responders, basic knowledge is needed about how the human eye works. Thus, this section presents a short description of the functionality of the human eye.

The condition of the visual system can be determined by examining various aspects of visual sensation. The ability to e.g. detect small objects (i.e. visual acuity) can be affected by disorders in the transparent media of the eye and/or visual nervous system. The inability to detect objects in specific areas of space (i.e. visual field defects) is often related to neural damage.

The visual field is the space perceived by a person when the eyes are in a fixed position, looking straight ahead. As the display in C Wear (Figure 4) only projects onto one eye, the discussion here relates to the aspects of the monocular visual field, as shown in Figure 5.

The monocular visual field is the area of space visible to one eye. It can be mapped parametrically, and perimetry testing provides a detailed map of the visual field. The potential visual field is described as a hemisphere. However, it does not form a perfect hemisphere, as the nose, brow, and cheeks occlude the view of the nasal, superior, and inferior areas, respectively, and the resulting monocular visual field occupies a limited portion (coloured grey in Figure 5) of the potential visual space. It also contains a 'blind spot', a small area located within the temporal hemifield, in which objects cannot be seen.



**Figure 5: The monocular visual field. Diagram: Penny AB.**

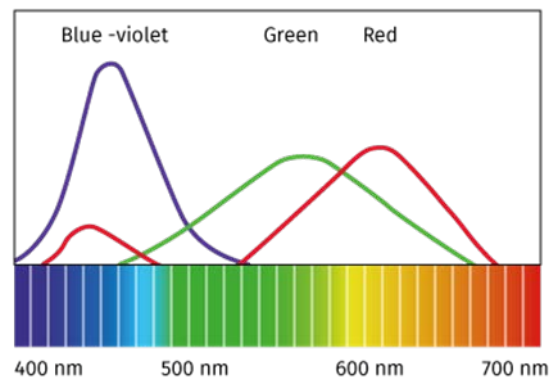
When light passes through the pupil and the lens, it stimulates receptors (rods and cones) on the retina, which send electrical signals to the brain. There are regional differences with regard to colour sensation, visual acuity, and low-illumination sensitivity within the visual field.

High illumination allows the visual field centre to operate at its most optimal, as it ensures the best possible function of the photopic subsystem (i.e. adaptation to relatively high illumination levels), which can be up to ten times better in terms of e.g. visual acuity and colour sensitivity than the peripheral visual field.

Vision in the peripheral visual field is more sensitive to dim light and operates reasonably well in low-illumination conditions, but has little colour-sensitivity and poor spatial acuity, as it represents the operation of the scotopic (dark-adapted) subsystem.

The human eye has four types of light receptor: Rods, which are sensitive only to black, white, and shades of grey, and cones, of which there are three types, each of which responds to a different range of colour. Rods are less precise than cones in their information-collecting ability with regard to small changes, e.g. in edge detection, and they respond only to light and dark, but are the only receptors which function at low light levels.

If a person moves from a well-lit area to one in which there is insufficient light for the cones to function, they are temporarily blinded. The rods start adapting to the lower levels of light available within a few minutes, however, and a considerable amount of vision is restored due to the rods' low-light response ability. Most of this adaptation occurs within five to seven minutes, but the process can continue for up to an hour. At these levels of light, the person is no longer able to see colours (as the cones do not work) and, because of the lower precision of rods relative to that of cones, edges are markedly less clear.

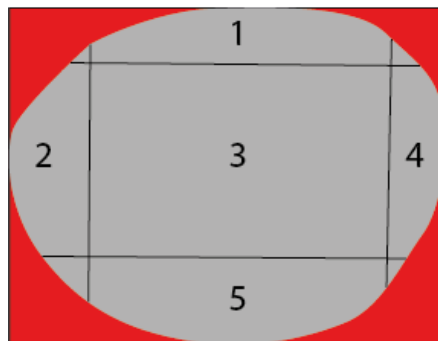


**Figure 6: The overlap of colour vision. Picture: Penny AB.**

At low-light levels, cones cease to function. Cones respond to different wavelengths of light as follows: 'red', 'green', and 'blue-violet'. In Figure 6, the overlap between the responses of the types of cones is shown. Bright green, yellow, and orange are the colours best perceived by the human eye.

### 6.2.3 The design of a user interface

As the graphical image of AR glasses is projected towards the human eye, the facts presented in the preceding section regarding the monocular field of view and the elliptical form of the visual field are also of relevance to how users perceive AR graphics. Figure 7 is an outline of the C Wear display. Based on the information given in the previous chapter, no information should be displayed in the red areas, as tests have shown that users generally cannot clearly see them.



**Figure 7: The display in C Wear. Picture: Penny AB.**

No objects that require any interaction from the user should be placed in Area 1 in Figure 7, and colourful and flashing objects should be avoided here as, if the eye looks directly at this area, the projection from the display no longer hits the retina. No important information should be placed in Area 2, as this would likely partially obstruct vision and irritate the user. Area 3 is the mid-field of vision, in which all situation-based graphics connected to collected information should be displayed, and no controls or actions not connected to the user's primary work task should be placed here. Area 4 is a suitable location for information relating to e.g. available air or other information obtained from sensors. In this area, flashing objects can be used to attract the user's attention, such as warnings of dangers to the individual or the group as a whole. Objects that involve some form of input on the part of the user can be placed in Area 5, and so buttons or navigation controls should be placed here.



One important aspect that should not be ignored when designing user interfaces (UIs) for transparent screens is that reality around the user becomes part of the actual interface and so, for AR, the requirements on the UI are very different from those related to other types of screens; it is very uncommon that it is possible to design a UI that follows traditional principles when one must take into account the objects in reality that the user may wish to interact with. Important considerations when designing first responder-related UIs are thus the content and placement of interactive elements. The following important parameters have been identified:

- In which of the five areas should blocks of controls be placed?
- How should the elements of controls be displayed?
- Should all blocks be transparent?
- What colours should the blocks be?
- What size should the blocks be?
- With what light intensity should the blocks be displayed?

The transparency in C Wear is controlled entirely by the design of the optical projection device, and dark colours are more transparent than bright ones. Black is wholly transparent, while white is near-opaque. If it is desirable to add graphics in Area 3, these should be darker so as to ensure that the user can see through them.

Further away from the centre of the eye's gaze a graphical object is placed, the more difficult it is for the user to recognise it. The size of objects in the upper, left, and right sectors of the display should therefore be increased as compared to ones at the centre or bottom of the display. Thus, an object in Areas 1, 2, or 4 should be double the size of one in 3 or 5.

## **7 Technology for underground positioning**

Safety in underground mining has developed in many areas over the last decades; improved air quality, measures to avoid falling rocks, and other technical solutions to enhance working conditions for underground workers. However, rescues of persons involved in underground disasters such as fires, gas leaks, or explosions still depend on very basic counter-measures, and many areas would benefit greatly from joint development.

Numerous systems for the surveillance or control of personnel in a tunnel or mine are based on traditional gate passage systems, controlled electronically or with manual lists. Considering the size and complexity of an underground mine, a gate passage system does not provide high accuracy regarding the whereabouts of personnel in an emergency situation.

At present, systems that facilitate the locating of persons more accurately are starting to be employed in some underground constructions, although these are not yet commonplace. A combination of good communication systems and positioning in real-time tracking systems will enable a radically new level of safety in the future.

### **7.1 A state-of-the-art system for positioning**

Positioning systems can be divided into three main types:

- Gate systems, which track an electronic tag as it passes through a gate.
- Continuous tracking systems, which follow a person, vehicle, or piece of equipment in real-time.
- Proximity systems; mainly used to guide autonomous vehicles.

#### **7.1.1 Gate system**

Tracking people using gate systems requires a gate receiver and a tag, which is attached to those who are allowed to pass the gate. There exist numerous commercial products for these systems, all of which use similar RFID (radio frequency identification) techniques with either active tags (battery-powered) or passive tags (no battery). The active RFID technique has the advantage that it has a greater range and can receive signals from e.g. someone in a car passing the gate, while the passive technique is more short-range and suitable for people walking through a gate. Common to both is that such a system offers a discrete observation of a position, which is known at the precise moment when the tag is logged at the gate but not updated until the tag is observed at the next gate.

Several gates can be used, but it is not cost-effective to sub-divide a tunnel using such a technique so as to obtain greater accuracy regarding positioning, even if some systems are based on tag readers that work within a distance of 50-100 metres. The primary drawback of such a system is its high cost, regarding both purchasing/installation and (more particularly) maintenance.

#### **7.1.2 Continuous tracking systems**

Real-time tracking systems are characterised by their ability to position in real- or near-real-time, and are based on various radio techniques with access points located between

100 and 300 metres apart. Vehicles or other objects can be positioned with radio tags, IP phones, or other equipment, which communicate on the radio network.

Currently, the most effective technique for underground systems is standard Wi-Fi-based radio networks. This is due to the fact that such a system gives a good, flexible communication network for both voice and data, the ability to position in real-time, and, more generally, the wide availability of standard Wi-Fi-based equipment. Positioning accuracy in these systems depends on the configuration of the Wi-Fi network and the use of algorithms. It is, however, difficult to obtain greater accuracy than a 25-50 metre area due to the variation in conditions in underground systems, relating to e.g. radio signal reflections and the blocking of signals by vehicles and pieces of equipment. Reducing the distance between radio access points is expensive, but does increase accuracy; a more cost-efficient solution is to use relatively low-cost beacons, placed between the normal Wi-Fi access points. With an accuracy of 25-50 metres, these systems are only of value during egress situations for personnel, rather than in positioning first responder activities.

Some systems use multiple radio frequencies; this offers an advantage as regards communication coverage, but has a drawback in that only equipment produced by one manufacturer can be used. To improve accuracy, additional techniques such as the two-way Time-of-Flight ranging scheme are needed, which can provide an accuracy of within one metre. More advanced equipment is more expensive, and is often less effective due to deficiencies in other functionalities, such as data bandwidth.

### **7.1.3 Proximity detection systems**

This pre-study does not cover proximity detection systems that have been developed primarily for use with autonomous vehicles and the detection of people close to the vehicle. Several manufacturers are in the process of developing new techniques that will facilitate their use during fire and rescue operations, particularly as remote-controlled firefighting vehicles.

### **7.1.4 Other positioning techniques and considerations**

Improved real-time tracking systems can be developed within wireless ad hoc networks. This is possible using new access points for communication and tracking purposes in an emergency situation. Some manufacturers supply fully ad hoc configurations which simplify positioning, while others need a greater level of manual setup. This pre-study has focused on localisation and communication using ad hoc RF networks (which have not been pre-installed) during fire and rescue operations, and the results are presented in the following section.

Other techniques for positioning and tracking, based on dead reckoning and similar methods, are under development or in a research development stage. Most of these systems are yet not ready for deployment for life-saving purposes.

## 8 Ad hoc RF networks

An ad hoc network is one which has been improvised using wireless nodes, each of which is independent of any fixed installation. Thus, the network topology is arranged incrementally by the network itself at the same time as the nodes of the network are distributed or established. This assumes that there is a gateway forming some kind of base station, as well as several initial anchor nodes with known positions and orientations. These nodes define a global coordinate system. ‘Ad hoc’ here implies that the network has a random structure, rather than a standard topology such as a star, ring, or mesh (Figure 8).

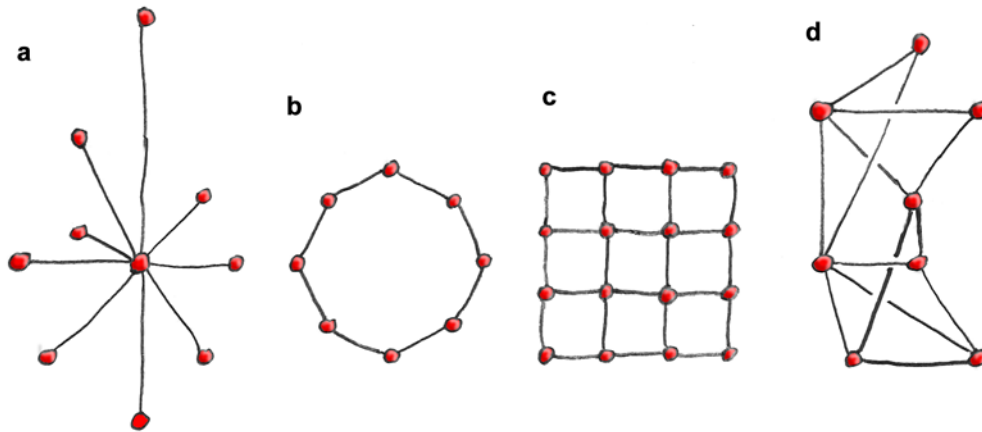


Figure 8: Network topologies. a: a star; b: a ring; c: a mesh; d: an ad hoc topology.

### 8.1 What are localisation and communication?

‘Positioning’ means identifying an object’s location in terms of  $x$ ,  $y$ , and  $z$  coordinates in a global coordinate system. ‘Localisation’ is an extension of positioning in which the object’s orientation (elevation,  $\theta$ , and azimuth,  $\phi$ ) is ascertained. In this report, in the interest of simplicity, both positioning and localisation proper are referred to by ‘localisation’; when a difference in meaning is significant, this will be pointed out explicitly. The focus of this pre-study is on two-dimensional localisation, a relatively simple scenario in which objects have only two position coordinates –  $x$  and  $y$  – and one orientation coordinate – the azimuth,  $\phi$ . Section 10, however, includes an extrapolation into three dimensions.

‘Communication’ means the one-way transmission of vital biometric and environmental data such as pulse, temperature, and remaining air supply. Also included in the concept is the two-way transmission of location data between nodes in the network. Audio or video communication are not included at this stage.

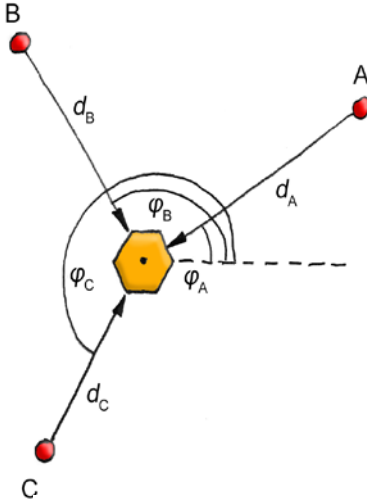
### 8.2 What is the problem?

A functional communication network is a prerequisite for localisation or positioning. It should, therefore, be assumed that the communication network is operational during a rescue operation. Here, only low-bandwidth communication, carrying information such as wind speed, temperature, remaining air supply, pulse, blood pressure, and body temperature is assumed. Video or audio communication, which require higher bitrates, are not considered here.

The overall goal is to ascertain the locations of all nodes by inter-node measurements and communication. Once these locations are found, nodes can detect the presence of nearby objects and report the locations of these as being similar to their own.

This main problem can be broken down into three sub-problems:

1. **Finding a suitable sensor.** A node needs some kind of sensor to measure its location in relation to its neighbours. Conceivable sensor modalities include IR light, sonar, and RF. With regard to the scope of this pre-study, environmental conditions such as smoke, dust, water, and ambient temperature make IR and sonar less attractive, and consequently the focus has been on RF as the medium of choice. An RF sensor is, quite simply, an antenna.
2. **Extracting local data from the sensor.** This includes bearings (i.e. angle-of-arrival; AoA) and distances (Figure 9). The sensor rarely delivers these directly, however, as they need to be computed. For RF communication, they can be computed using e.g. received signal strength indicator (RSSI) values, time of flight (TOF), or time difference of arrival (TDOA).



**Figure 9: Local measurements.** Angles of arrival and distances between neighbours are illustrated.

3. **Computing location in the global coordinate system from local bearings and distances.** Localisation in the global coordinate system combines local and pairwise measurements of bearing and distances. This requires a coordinated operation across the whole network. The computation of orientations necessarily requires bearing data, which is not always easy to obtain. However, orientations may not be of crucial importance in some cases.

## 8.3 User requirements

Essential to the design of the localisation system are user requirements, which can be divided into primary and secondary requirements.

### 8.3.1 Primary requirements

**Accuracy.** The accuracy should be 5-10 m [19].

**Response time.** The time until a node knows its location with acceptable accuracy: This should be less than the time it takes to walk from one node to the next. Assuming that nodes are located approximately 12 m apart, the response time should be less than 30 s [19].

**Size.** The nodes should be small enough that a sufficient number of them can be carried and distributed easily by one person (approximately the size of a hockey puck).

**Reliability/robustness.** The nodes should be resistant to water (IP65-IP67) and heat, within reason, as rescuers are not allowed to proceed without working communication [19].

### 8.3.2 Secondary requirements

**Battery duration.** Batteries should last at least 48 hours [19]. This is considerably more lenient than what is usually the case for wireless sensor networks, where an operating time in the order of years is expected.

**Cost.** The cost should be sufficiently low that the possibility of damage to several or even all nodes should not cause users to hesitate to deploy them. The cost limit is estimated to be roughly 1000 SEK per node.

## 8.4 Available commercial solutions

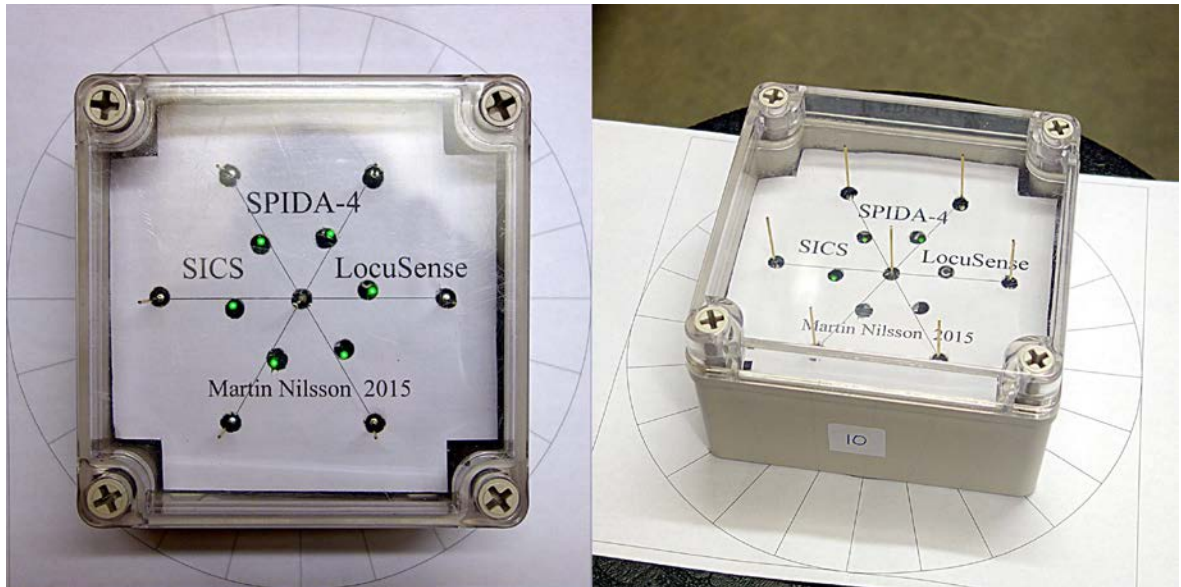
The problem of localisation/positioning is currently receiving an enormous amount of attention, most likely driven by applications such as mapping the traffic patterns of consumers in shopping centres. However, commercially available solutions are almost exclusively based not on ad hoc networks, but on pre-installed and calibrated networks of nodes, which measure the locations of objects moving within these networks. In other words, almost all solutions focus on Sub-Problems 1 (sensors) and 2 (ascertaining bearing and distance), ignoring Sub-Problem 3 (global localisation). A common solution is to use commercial off-the-shelf (COTS) Wi-Fi access points that have not been optimised for positioning. Using simple estimates based on RSSI levels, accuracies of 50-100 m can be achieved for access points spaced at 400 m intervals, and newer techniques capable of accuracies of 25-50 m are currently being tested [20]. Fingerprinting techniques [21] can increase accuracy, but the best results reported so far use multi-antenna, multi-subcarrier Wi-Fi nodes, and are able to achieve an accuracy of less than one metre [21]. However, such accuracies require a relatively high density of Wi-Fi access points. Systems using preset UWB nodes are also commercially available, e.g. the BeSpoon system [22].

Systems that utilise fully ad hoc networks in localisation, i.e., those which solve Sub-Problem 3, are much more difficult to find. A difficulty here is that errors in location estimates can be propagated, causing estimates to drift; in the worst case, the error may be fed back and amplified, resulting in instability. At present, the research field is primarily active within academia, but a first step of this pre-study was to tentatively evaluate two promising techniques. The first of these uses narrow-band radio, and the second UWB.

### 8.4.1 Candidate 1 (C1): LOCUS with a SPIDA-4 antenna

LOCUS is a distributed algorithm that uses AoA information and optional distance information for localisation [23]. It is based on a distributed linear Kalman filter (LKF) [24] and is resistant to noise. LOCUS solves Sub-Problem 3, but is critically dependent

on AoA values. As a sensor, the most recent version (v.4) of the SPIDA smart antenna [25], kindly provided by LocuSense AB, was used. These SPIDA-4 antennas use COTS OpenMote nodes with narrow-band 2.4 GHz CC2538 radio chips [26]. The entire system, including antenna, CPU, and batteries, encased in an IP67 waterproof box, is shown in Figure 10.

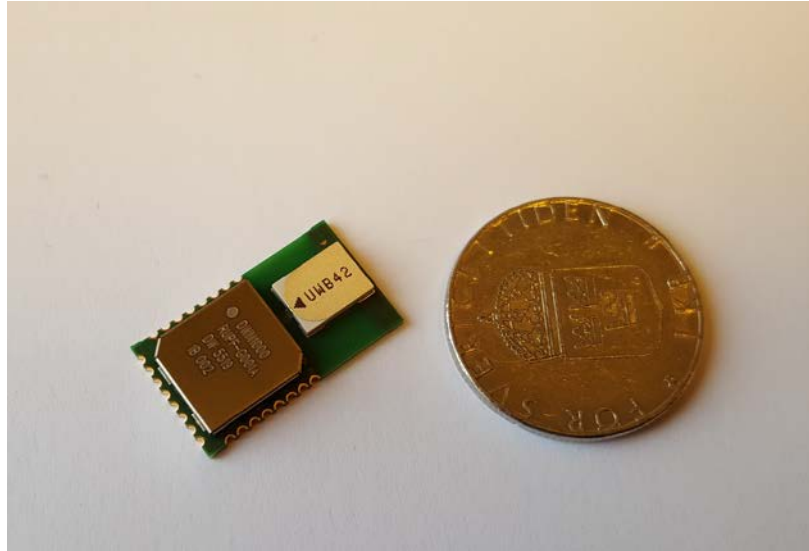


**Figure 10: Boxed node.** The waterproof box contains a SPIDA-4 antenna, an OpenMote CPU card, a power supply consisting of one or two AA batteries, and a magnetic on/off toggle switch.

The node can be switched on and off, without opening the box, using a magnet. Out of the series of 25 built, five included a powerful Cortex-M4 processor with floating-point instructions. The remaining 20 use the simpler Cortex-M3 processor, available on the OpenMote board.

#### 8.4.2 Candidate 2 (C2): DecaWave UWB module

The second alternative (see Figure 11) was the recently (2014) released COTS DecaWave UWB module DWM1000 [27]. This module can only measure distances, and so cannot support the computing of orientations. An efficient method for computing positions from distance measurements is the well-known GPS method, which uses extended Kalman filters (EKF) [24]. For solving Sub-Problem 3, Zachariah et al. recently proposed a new method [28].



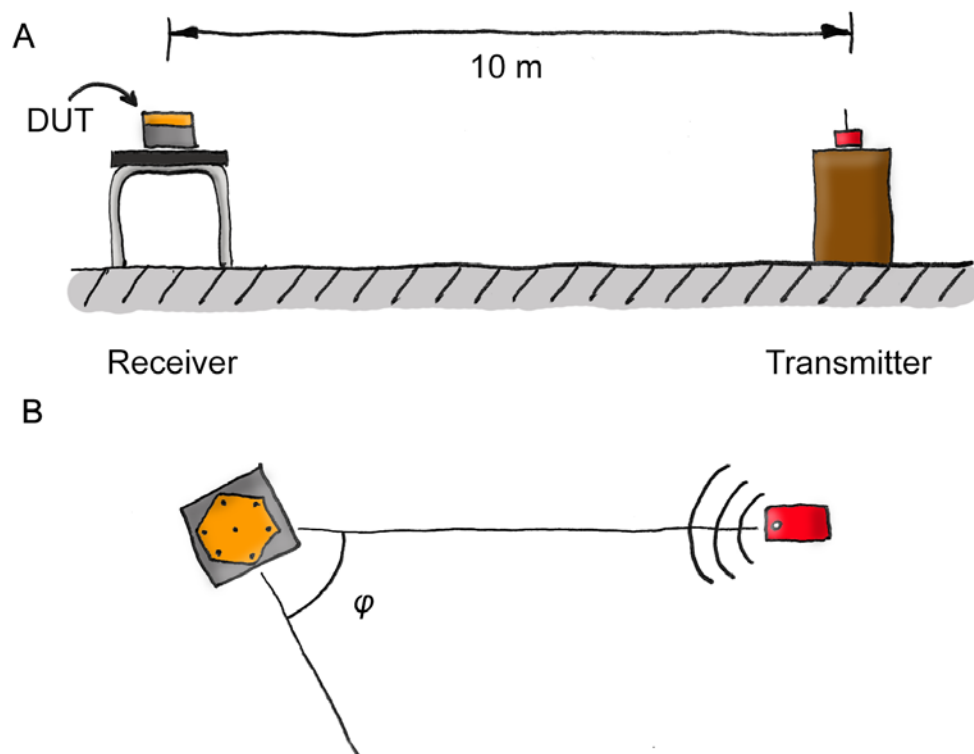
**Figure 11: DecaWave DWM1000 UWB module, with a Swedish krona next to it for scale.**



## 9 Measurements in relation to requirements

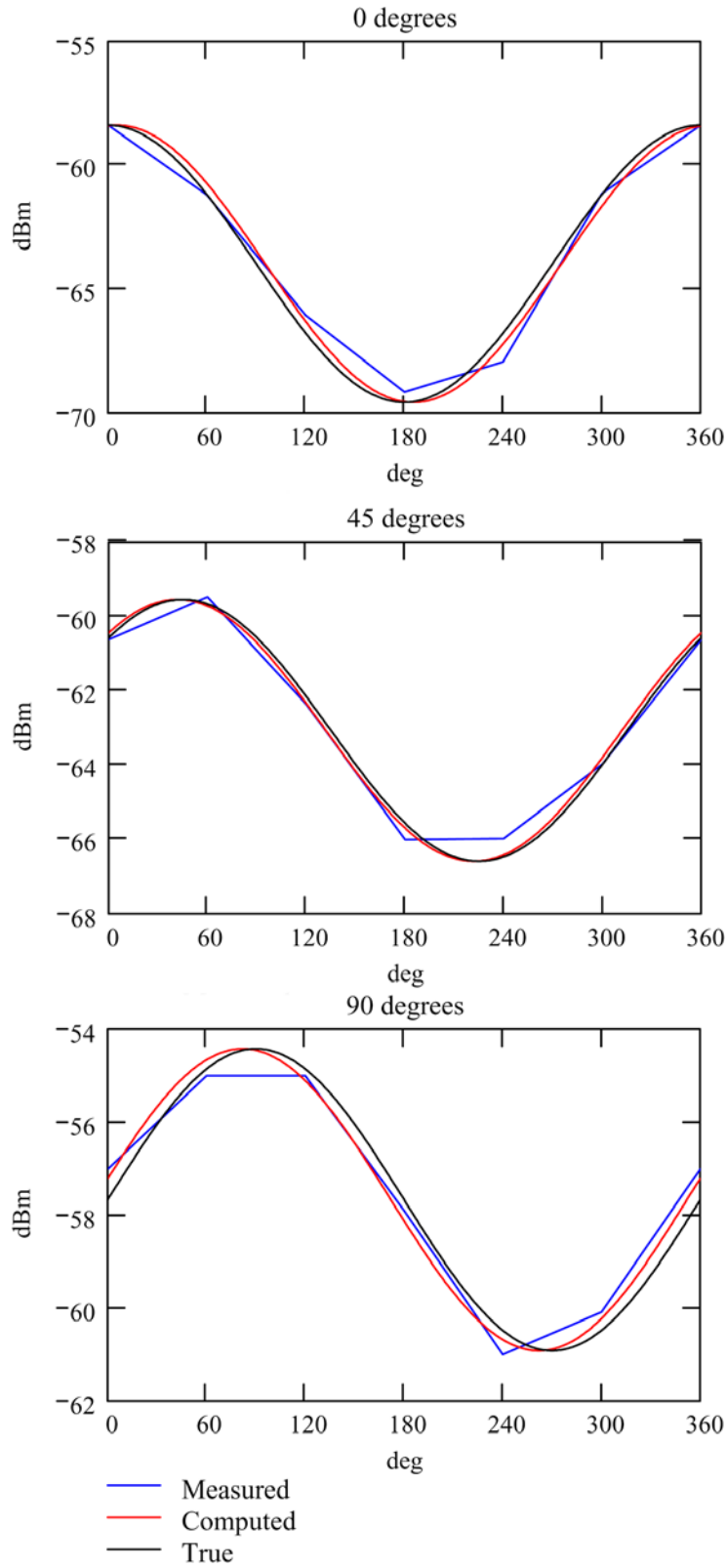
### 9.1 Preliminary measurements

For the narrow-band C1, the LOCUS method rather neatly solves Sub-Problem 3 by providing solutions to Sub-Problems 1 and 2 [23]. Here, the critical issue is how AoA readings can be obtained. SPIDA-4 measures the direction of an incoming message by combining RSSI values from six different directions.



**Figure 12: Angle-of-arrival (AoA) measurement setup.** The DUT (device under test) is a box containing a SPIDA-4 antenna, an OpenMote CPU board, a battery-driven power supply, and reed switches for turning the device on and off using magnets.

The first major task was to investigate both the reliability of communication and the antenna gain underground. This was tested in both the Kristineberg mine (sphalerite, chalcopyrite, galena; ~800 m depth) in Boliden and the Tistbrottet mine (dolomite; ~50 m depth) in Sala.

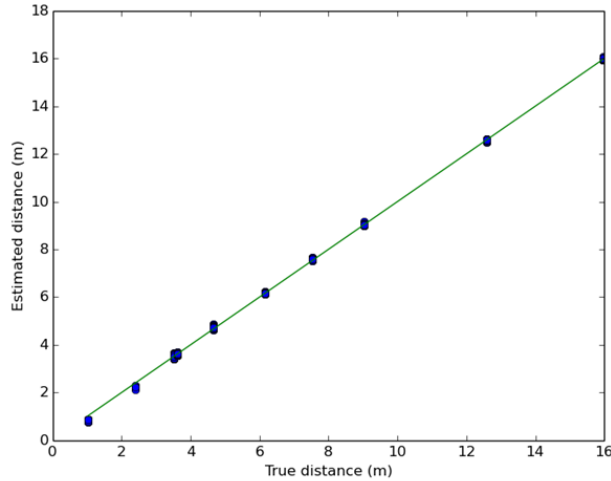


**Figure 13: Measurements for 0°, 45°, and 90° AoA. Measured AoA are 5.4°, 41.9°, and 82.0°, respectively. The AoA is computed as the phase difference between a nominal cosine and a cosine fitted to the RSSI values received by the SPIDA antenna [24].**

It was found that communication is highly reliable for distances well beyond a 20 m line-of-sight (LoS) at low RF power ( $\leq 1$  mW). External noise is very low, but there is a fair amount of reflection, and tests confirm that mine shafts appear to have a tendency to function as wave guides, as has been suggested by other researchers. The antenna gain was also investigated in both Kristineberg and Tistbrottet and found to be 5-6 dBm, which is an acceptable value.

The second major task was to measure the accuracy of AoA measurements. Testing was performed in a laboratory environment with dense reflections, where a boxed receiver was set up at a variety of angles at a distance of 10 m from a transmitter (Figure 12). The receiver was set at  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$  so as to test for a representative selection of angles, and it was possible to measure AoA with an error of less than  $10^\circ$  (Figure 13), which is quite sufficient for the application of LOCUS. However, it was found to be necessary to measure across all 16 available frequencies (channels) in order to achieve this accuracy. This meant that approximately 15 minutes were required to obtain a single AoA reading, a somewhat disappointing time in relation to the necessary response time for a rescue operation.

For C2, only the data acquisition speed of an unboxed module was tested. This measurement was very fast; roughly one second. The experiment was divided into Line-of-Sight (LoS) and non-Line-of-Sight (nLoS) measurements (Figures 14 and 15, respectively). For the LoS measurements the ranging errors were all under 0.3 m, and typically under 0.10 m. For the nLoS measurements, the worst-case errors increased to approximately 2.5 m, but typical errors were under 1 m. However, as can be seen in the figures, the variance for measurements taken at the same location is higher for nLoS measurements than for LoS measurements. This can be used to identify nLoS conditions and compensate for such measurements, as has been reported previously [29]. Figure 16 shows the errors for all measured distances (both LoS and nLoS), with and without this compensation. The results show that large errors, due to nLoS conditions, can be decreased significantly.



**Figure 14: UWB accuracy, Line-of-Sight (LoS).**

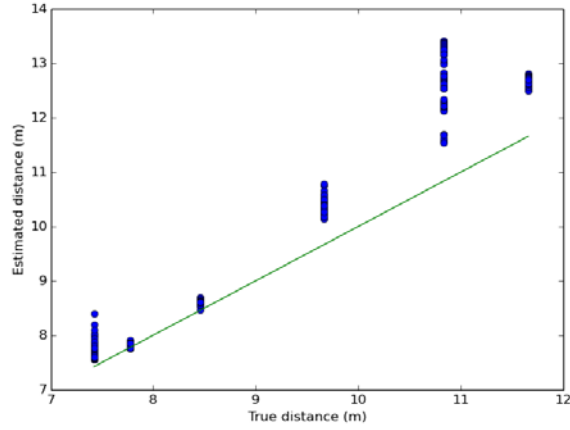


Figure 15: UWB accuracy, non-Line-of-Sight (nLoS).

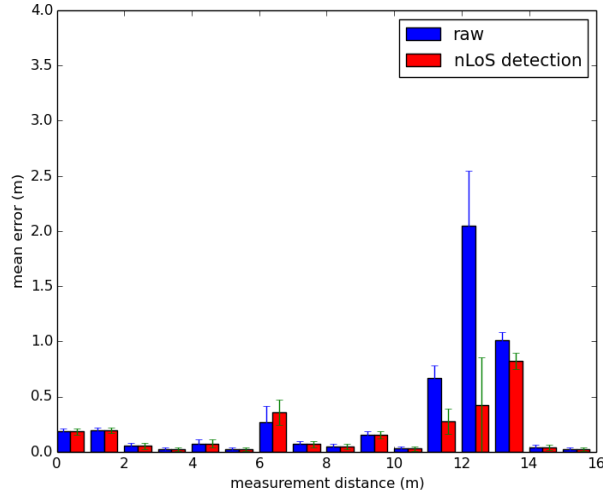


Figure 16: UWB accuracy, with nLoS detection. The blue bars show both LoS and nLoS combined, while red bars have detectable nLoS excess removed.

## 9.2 Evaluation of the performed tests

### 9.2.1 Primary requirements

**Accuracy.** Based on the tests, it is estimated that both C1 and C2 networks satisfy the accuracy requirement of an error margin of 5-10 m (cf. Table 1). Here, it is assumed that networks of up to 20 nodes are laid out in an approximately even manner, in a zigzag pattern along the path of penetration (Figure 8d) and covering a total distance of 100 m. It is also assumed that nodes are located approximately 12 m apart, and that one node can ‘hear’ at least three previously placed nodes.

**Response time.** The response time differs considerably between the nodes. Experiments clearly demonstrated that C1 nodes must use multiple channels to obtain good AoA values. Finding one such AoA value required 15 minutes, which is far too long. The C2

nodes, on the other hand, could achieve a distance reading very quickly – within one second.

**Size.** Due to the laws of physics, the SPIDA antenna needs to be roughly the size of a wavelength in order to be efficient. At 2.4 GHz, this would require a box with a diameter of approximately 12 cm, which would be somewhat large for a ‘hockey puck’. The UWB antenna of the C2 node can be made much smaller and, although the Decawave module was unboxed in the pre-study, a full system based on this module could definitely be produced and be the size of a hockey puck.

**Reliability/robustness.** Enclosing C1 in a watertight box did not result in any adverse effects. The antenna gain was roughly the same inside the box as outside it (5-6 dBm). The communication tests (using an ordinary quarter-wave antenna) in the mines showed that communication was highly reliable. SPIDA tests in the mine showed that the antenna gain was acceptable (5-6 dBm), and that there were no problems with homogeneous fields or noise.

## 9.2.2 Secondary requirements

**Battery duration.** The battery consumption of C1 was small, in the order of a few mA. On the other hand, the battery consumption of C2 was much greater, at 160 mA, corresponding to 7.7 Ah for a duration of 48 hours if used continuously.

**Cost.** It is estimated that the materials and manufacturing costs for both C1 and C2 nodes would be less than 1000 SEK for series production, which is within the specified price range of this study.

The evaluation is summarised in Table 1.

**Table 1: Comparison of narrow-band and UWB alternatives.**

	Narrow-band (C1)	UWB (C2)
Accuracy for distance between neighbours; 1 hop	~1.5 m	~0.3 m
Response time for 1 hop	~16 min	~1 s
Diameter	~12 cm	~4 cm
Reliability of communication	acceptable	N/A
Power consumption, active	~5 mW	~500mW
Cost	<1000 SEK/node	<1000 SEK/node
Computes orientation	Yes	No

## 10 Conclusions

Tests have been carried out in existing mining environments and complex office corridors with conditions resembling those of a mine. Tests have also been carried out in collaboration with fire and rescue services in order to identify equipment and wearable technologies that could support and make fire and rescue operations in mines and other complex underground constructions safer and more efficient. A computer application for digital simulation has been developed and adapted to the system, although this only operates on a relatively basic level, so as to support the testing of the positioning and communication systems; thus, more can be done to improve performance for real-life applications. The analysis was conducted by studying the results of the experiments and linking them to expected usage during a fire and rescue operation.

The evaluation of two types of system, C1 and C2, shows that response time is a critical factor. For C1, the ascertaining of AoA is too slow with regard to user requirements, as many channels have to be measured sequentially. With a UWB node, distance measurements can be acquired almost instantly. In principle, UWB also uses multiple ‘channels’ (i.e. sub-frequencies), but measures them all simultaneously. There are two major disadvantages with UWB, however: Firstly, it cannot compute orientation, only position – although this may not be a problem with regard to the intended application. Secondly, UWB consumes a great deal of power, although if it is only used for localisation (leaving narrow-band for communication purposes), this is perhaps not a problem either. An attractive advantage of UWB is that such a sensor can easily be generalised to localisation in three dimensions; this is less achievable for narrow-band antennas, which cannot be made isotropic due to the fundamental laws of physics.

The final conclusion is that, at this time and for this application, the UWB solution (C2) seems to be preferable. However, the development of UWB technology is proceeding at a rapid pace, and it is clear that UWB modules able to compute AoA may be available in the near future. When this happens, a strong candidate would be a combination of LOCUS with AoA-computing UWB nodes, which would offer the best of the two approaches.

Although audio and video communication are not considered in this pre-study, it is conceivable that an ad hoc network could additionally serve as a backup for the RAKEL communication system when repeaters for direct mode (RMO) are unavailable. It therefore seems that a promising direction for further investigation is the feasibility of ad hoc networks for rescue services, rather than only for localisation. Moreover, RAKEL has a limited bandwidth that only allows for relatively low data rates. This has been identified by the Swedish Civil Contingencies Agency (MSB) as a shortcoming of the system, and efforts have been made to investigate ways of enabling higher data rates. However, no clear solution has yet been discovered.

The interviews performed within the pre-study all indicate that the bottleneck encountered in efforts to improve safety and efficiency in underground fire and rescue operations is related to the lack of robust and reliable possibilities for positioning and connectivity in complex environments. The development of new technologies for first responder support should therefore preferably be linked to a parallel development of safe systems for positioning, communication, and information exchange with possibilities to transmit both audio and video information.

## 11 Future research

This pre-study has provided valuable information regarding which systems should be further developed, and which should not be used for this application. The results can provide for future system design, with more accurate positioning and improved connectivity. The positioning and connectivity techniques can be used as part of both fixed installations and ad hoc systems. Ad hoc systems can be used for backing up existing systems, or in ones in which the technology is not pre-installed. Wearable technology and intervention-support equipment that can make full use of these improved conditions will enhance the safety and effectiveness of fire and rescue operations, and should be further investigated and adapted to the new possibilities.

The main tasks which would best be served by coordinated research and development actions so as to improve safety and efficiency during fire and rescue operations in mines are:

- Further research and development to improve accuracy to <1 metre, preferably through further investigation of UWB techniques.
- Improvements in connectivity in order to facilitate better information exchange between the scene of the fire and the Command and Control Centre.
- Evaluation of oxygen systems for fire and rescue operations with long response routes.
- Improvements to BA oxygen system performance regarding e.g. humidity and equipment design.
- Development of AR equipment for use by first responders.
- Development of technology with which to survey physical conditions using intelligent textiles or wearable technologies.
- Improvements to integrated IR imaging for BA firefighters.
- Investigation of the possibilities for interaction with or sole use of remote-controlled fire and rescue vehicles.

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