Mining Ventilation Automation: Wireless Sensing, Communication Architecture and Advanced Services

CONFERENCE PAPER · SEPTEMBER 2008

DOI: 10.1109/COASE.2008.4626510 · Source: IEEE Xplore

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Mining Ventilation Automation: Wireless Sensing, Communication Architecture and Advanced Services

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***Abstract*—This paper reports on the definition of technical challenges for the sensing and communication networks of a mining ventilation automation project. Specifically, complex network architectures offering high performance are investigated. The aim is to support distributed estimation, and to propose an enhanced architecture for advanced services in the mining context, namely positioning and audio/video communications. Then, analytical models are developed to "expose" network performance to the control application, and a service platform is suggested to encapsulate all essential services that the network should provide to the distributed control application. Specific results are provided for the positioning service.**

I. Background and Motivations

Mining ventilation is an interesting example of a large scale system with high environmental impact. Exploitation of communication architectures in the underground process, to provide distributed sensing/actuation capabilities and more advanced services, leads a mining operating site to become a very large interconnected system. Advanced control strategies can take significant benefit from a flexible network, which enables us to increase safety of human operators and efficiency of the overall system.

Research challenges the main architectural components of a mining ventilation control system have been described in [1]. In this position paper, we are specifically concerned with the underlying sensing and communication architecture. Specifically, we investigate on the communication architecture needed to support control and safety in the wireless automation for the mining ventilation process. A design space exploration is presented to highlight costs and benefits of different approaches, and considering also future needs related to the automation process as well as to the potential provision of advanced services (e.g., localization, audio, etc.).

Typical existing ventilation control systems are either poor or non existing. A continuous monitoring of air quality is absent, and the only communication capability is simply voice over walkie-talkie. The amount of air pumped in the rooms is manually controlled in open-loop, and safety is guaranteed with a huge margin. Therefore, it is clear that investigating about a communication architecture able to support distributed sensing/actuation tasks for automatic control solutions of the amount of pumped air is of great environmental and industrial interest, since it allows for saving energy consumption. An additional system objective is to obtain safety through wireless networking for personal communication and localization. It should be noted that today's control architecture does not enable the fulfillment of these objectives, since there is neither automatic control (maximum actuation during ore extraction), nor sensing capabilities (physical/chemical measurements or localization) and limited communication opportunities. The proposed wireless communication architecture aims at providing an effective support to the development of a control strategy able to fulfill all the objectives listed above. In particular, we will be concerned with the design of the secondary system (extraction rooms), which poses the most serious challenges in terms of scalability, variability and reconfigurability.

The paper is organized as follows. Section II describes the proposed alternatives for sensing and communications architectures. Section III is concerned with definition of algorithms and fundamental modeling for distributed processing and networking protocols. In Section IV the definition of a platform concept for advanced services is presented. Further details of algorithms and procedures for development of a localization service component are presented in Section V. Conclusions and future perspectives are outlined in Section VI.

This work has been supported in part by the European Commission through the FP6 NoE project HYCON.

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II. Communication Architecture

The primary need for ventilation control is to obtain information about air pressure and temperature in the Ventilation shaft, Truck access tunnel and Extraction rooms. Using this information, a control strategy suitable to maintain environmental parameters within specified ranges can be applied. Moreover, for Truck access tunnel and Extraction rooms (secondary system) measurements are required for NOx and CO concentration. The proposed communication architecture is depicted in Figure 1, where networked sensors are envisaged in the vertical ventilation shaft, in access tunnels and in the extraction rooms. The basic architecture of this wireless sensor network (WSN) thus includes fixed wireless sensor nodes along the vertical shaft in the primary system and mobile wireless sensor nodes in the secondary system. Operation of the latter nodes is of major interest when trucks are working within the extraction rooms. This sensing (lower tier) network has to be complemented by a communication network portion, which is in charge of delivering information over longer ranges, up to controllers and actuators. As different opportunities can be considered in this regard, some alternatives are briefly described in the following.

A. Uniform Radio Network

Assume that the same radio technology (e.g., IEEE 802.15.4 [2]) is adopted in the whole system, both in the lower (sensing) tier and in the interconnection portion.

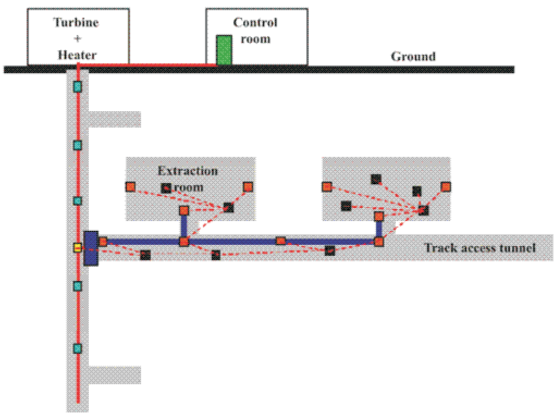

Fig. 1. Sketch of the mining scenario and main network components.

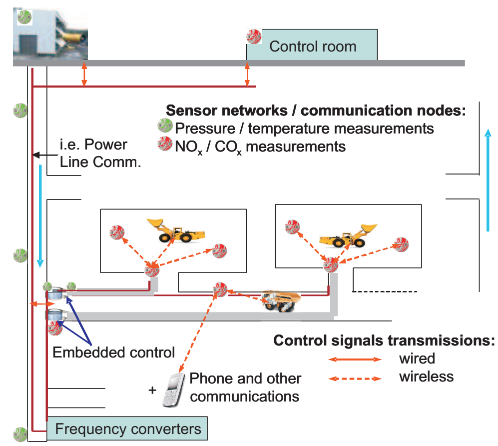

Fig. 2. Dynamic wireless backbone with heterogeneous technologies.

Interaction with the existing mining infrastructure is minimal and we can devise two major patches of nodes: one for the primary system, which appears as an ad hoc multi-hop network with fixed topology, and one for the secondary system, which appears as an ad hoc multi-hop network with partially varying topology. Topology variation may be induced in a shorter time scale by movements of trucks within an extraction room or when they move along tunnels and/or from one room to another. The set of (relaying) nodes installed along the tunnel can be fixed and located at proper distances in order to provide continuity of radio coverage along the whole tunnel. On a longer time scale, the topology variation might be essentially related to the size of tunnels and the number of extraction rooms: as the mining extraction works progress, the tunnel length and the number of rooms rises, with the consequent increase in the wireless network size.

This induces certainly an impact in scalability of solutions, because a larger size implies larger number of hops, longer delays and larger traffic to be supported by relaying nodes. Finally, it should be pointed out that in this architecture the mobile nodes might not be subjected to severe energy constrained operations, since they can either rely on local power generation mechanisms or be maintained by people when they come to ground level. On the contrary, the wireless nodes deployed on those portions of tunnels where electrical cabling is absent might be battery powered or provided with energy scavenging, but not able to benefit from typical recharge facilities.

B. Hybrid Wired-Wireless Architecture

Since the whole system setup foresees the presence of some cabling, e.g., for power delivery to fans along the primary system, and for connecting entrance detectors in rooms in the secondary system, it is interesting to investigate power line communication (PLC) devices for setting up the interconnection network. The main idea is to provide a wired backbone along the power line already present in the system to connect the Control Room with an 802.15.4 WSN. In this setup a proper PLC/802.15.4 Gateway should be deployed at the intersection between the Ventilation shaft and each Truck access tunnel. The gateway is also provided with pressure and temperature sensors, and it acts as a sink node for the two main patches of wireless sensor nodes described before. As for energy provision to the network nodes, there are no additional remarks with respect to the case with uniform radio technology described before.

C. Extended mobile wireless architecture

The basic setup depicted so far can be enhanced by further exploiting the fact that the working environment is typically populated by several mobile entities like trucks and humans. Such entities (let them be equipped with one or more sensor nodes) could be useful to improve the quality of monitoring by increasing the spatial density of measurements. While the mobile entities are a potential benefit from an energy point of view (as the wireless nodes can resort to classical battery recharge mechanisms), their deployment poses additional challenges as it induces a increase of topology variability in space and time. Along that line, an interesting evolution is concerned with hand-held and/or on truck mobile nodes acting as clusterheads and in turn interconnected (e.g., through an IEEE 802.11 protocol) to build a dynamic wireless backbone (see Figure 2): this would help to make energy constraints on some lower tier wireless sensor nodes less stringent, while providing a larger bandwidth support for introducing advanced services, as it shall be devised in Section IV.

III. Models And Algorithms

A. Distributed Estimation through Wireless Sensors

We have already emphasized that a fundamental ability that is required to the (lower tier) wireless sensor network deployment is to provide a set of distributed measurements within the extraction rooms, so that an estimate of the air quality can be achieved by, e.g., average estimate. On this subject we can resort to recent advances on distributed estimation and control algorithms, which account for limited power, computing and communication capabilities.

A typical paradigm consists in using local information, while it can be observed that suitable cooperations among neighboring nodes can improve the estimation quality considerably. Using sensor readings from more than one sensor can overcome intrinsic performance limitations due to bias, uncertainty, and noise that may affect an individual device. The characteristics of the wireless propagation make it natural to exploit cooperative schemes for estimation. These approaches are in contrast to the traditional architecture with sensors, which simply provide raw data to a fusion center. By letting the network do the computations, it is possible to reach a more scalable, fault tolerant and flexible design. Despite current research activity and major progress, the theoretical understanding is far from satisfactory of these systems, which are exposed to link and node failures, packet drops, restricted power consumption etc.

In many relevant contributions related to distributed estimation, a common strategy is computing the average of the initial condition of the state of a set of nodes of a WSN. In these algorithms, called consensus strategies (e.g., [3]), each node takes a set of initial samples, and then iteratively exchange the averages of the samples collected by other nodes so that each node reaches asymptotically the global average. We design a patch of wireless sensors and the related algorithm based on such an estimation approach, which can provide us with the average concentration of gases in the room with a given accuracy. The availability of sensors on trucks is accounted for. Results have been achieved for a movable grid of sensors and some experimental results have been obtained in lab facilities with light sensing elements. To a larger extent the approach encompasses the distributed positioning problem that is discussed later in this paper.

B. *Latency and Energy Models in Multi-hop Networks*

The sensors in a room can be seen as a cluster with a cluster-head at the room entrance, while the gateway is now closer to the fan and can be reached by a multi-hop wireless backbone. The latter one can also implement further sensing capabilities within the tunnel. The wireless network is therefore a clustered network. In the depicted context it becomes important to deal with network delays for closed-loop analysis and with energy consumption concerns for network lifetime with limited maintenance.

A model for end-to-end delay is proposed here and accounts for i) a time-varying number of nodes composing the path between the source and the destination, ii) the time to wait before sending a packet, iii) the time to forward a packet to a given neighboring node, and, finally, iv) the delay induced by an Automatic Repeat Request (ARQ) mechanism. This high level model can be further refined using a more structured design and introducing some topological details. In the literature there exists a variety of protocol-dependent latency models, (e.g., in [4] and references therein). Our current activity is concerned with performance analysis of closed-loop control over a multi-hop network, by resorting to the delay analysis, protocol operation and related tuning of SERAN protocol [5] in the specific network context of this mining test case. The activity is complemented by experimental trials on a scaled model.

Since energy efficiency is also a concern, algorithm and protocol design are required to minimize energy consumption for

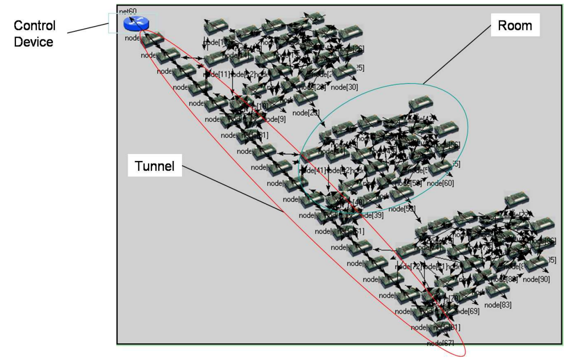

Fig. 3. A sketch of the developed OMNeT++ simulation scenario.

maximizing network lifetime and/or minimize maintenance. There is a rich set of examples in the recent literature with a variety of proposals: the policies to control the transmit power of the inter-node transmissions while maintaining a sufficient reliability level of the communications, e.g., [6], communication protocols which aim to minimize the number of collisions and thus the retransmissions or to find the routing paths including the energy spent in their metric costs as well as position information to reach the destination with less number of hops [7]. Further to exploration of protocol alternatives for the mining ventilation context, we have been concerned with development of energy models for currently available WSN platform. In fact, in [8] an energy model for the Chipcon CC2420 radio chip [9], embedded on the Crossbow's Motes [10], has been developed. In particular, our models take into account not only the energy spent in the transmission and reception states, but also the energy required for the transitions from these states and the idle or power down states.

In the particular frame of our mining ventilation test case, we aim at developing a consistent framework for supporting performance analysis and validation of control algorithms, with hopefully a close bridge to protocol synthesis. We have then developed simulation environments that support accurate description of the models discussed above. Two discrete event simulator have been setup, by resorting to OMNeT++ [11] and DESYRE [12]. An OMNeT++ schematic is sketched in Figure 3, and we were able to obtain results that evidence energy depletion and latency behaviors.

IV. Advanced Network Architecture and Services

A. *Heterogeneous Radio Technology*

While the architecture and algorithmic components presented so far are intended to support the basic application of ventilation control, we already mentioned in Section II that further exploitation of wireless technologies and advanced network architectures might provide support for further applications. For example, in order to support voice and video communications, LAN and WLAN technologies are appealing, with deployment of nodes where energy is not a major concern (e.g., mobile gateways on trucks or on palmtops) and exploitation of ad hoc mesh networking.

We are then concerned with heterogeneous radio technologies, by introducing e.g., IEEE 802.11 in ad hoc version in

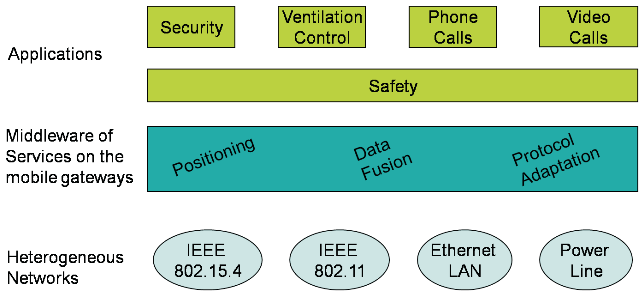

Fig. 4. The platform.

order to provide lager bandwidth and longer hop-ranges in the wireless relaying part of the secondary system. This kind of architecture resorts on the fact that mobile entities can be considered as non energy-constrained and are then able to support power expensive wireless radio technologies. This solution explicitly accounts for the presence of mobile gateways and introduces shorter-term topology variation also in the interconnection portion of the wireless network deployed in the secondary system.

B. Advanced services

1) Localization: The presence of mobile nodes in the system lead to consider other services, besides monitoring. The localization service is of particular interest for the considered scenario and it would be limited, at a first instance, to provide the tunnel/room coordinates for mobile entities located in an Extraction room, and the tunnel/linear position along the tunnel coordinates for those located in a Truck access tunnel. However, a perspective view is to deploy a localization services that allows for tracking the position of machines and operators within the whole mining area, including declines and also outdoor area.

2) Voice: While the localization service could be provided by exploiting the basic uniform network architecture, there are other services that requires the advanced architecture. One opportunity is represented by an IP-based (peer-to-peer) voice service, whose effective deployment would require the heterogeneous wireless network (IEEE 802.11 and IEEE 802.15.4).

C. A Longer Term View

A longer term view, beyond the simple support for automatic ventilation, can be cast in terms of development of a platform concept, as depicted in Figure 4. It foresees added value applications, like security in terms a gate access monitoring, video and phone calls as well as control and safety checks, and resort on a flexible middleware layer that integrates positioning, data fusion and protocol adaptation. The platform implicitly assumes the network heterogeneity outlined before.

V. Case Study: Localization Service

Several contribution for geolocation in mines have been proposed (see, e.g., [13], [14], [15] and references therein). In particular, in [13], the authors investigate the main sources of positioning errors: the classical ranging methods, such as Time of Arrival or Received Signal Strength, produce unreliable distance measurements, especially in indoor environments. They propose a pattern matching localization technique, where a mobile station matches on-line wide band channel observations with the learned set of off-line “signatures”, accurately locate its position, typically with an error less of 2 meters in 90 % of cases. In [14] and [15] an experimental study of the ultra wide band (UWB) radio channel in underground mines is presented. Results show that UWB is a potential candidate as physical layer for wireless in underground mines either for achieving accurate position estimations via time-of-arrival measurements or even RF fingerprint techniques, as well as for reliable communications.

In this section we show how to design a Location Service (LS) for wireless sensor networks, adopting a Platform Based Design approach. We define the Location Service as a procedure that collects and provides information on the spatial position of the nodes in the network. A point location is defined as a t-ple of values, which identifies the position of the node within a reference system. Assuming a Cartesian common reference system, a location is a struct-type collecting fields as x, y and z, a scale factor, which defines the resolution, and an accuracy level, which allows us to associate a reliability indicator to a position estimation. Details are discussed in the following.

At the application level, we consider a function *struct location Localization()*: it consists simply in the attempt of each node to be aware of its position as soon as it starts operating into the network. In defining this interface (and the richness of related set of primitives), we refer to the class of distributed and cooperative algorithms [16] and [17]. These algorithms assume the presence of a certain (possibly low) percentage of anchor nodes, which know their position with very high accuracy. We also assume a static context. A subset of primitives is listed and briefly described in the following, while the complete list is provided in [18].

- *float distance LAGetRange(int NodeID)* operates a cooperative ranging procedure between a node and the neighbor having $ID = NodeID$, where $NodeID$ denotes a node identifier;
- *struct location LAInitialEstimation()* returns the initial position estimation according to a predefined criterion. Alternatives for initial estimation include the simplest random guess, as well as a smarter, but more expensive, solution like Hop-TERRAIN [19];
- *struct location LAStep(struct location *arrNeighsLoc, struct refinementParameters par, int Time Tup)* proceeds one step ahead with the positioning algorithm once new information about positions of neighbors is collected. It returns the new estimation of the position of the present node. When the STOP criterion is reached, a flag is set that enables broadcasting of position information;
- *void LABroadcast(struct location *loc)* broadcasts locally the present position and accuracy of the estimate as well;
- *LACoordination(struct location *loc)* is invoked when a node with insufficient connectivity cannot resolve an ambiguity in position estimation and requires cooperation

of its neighbors.

A. Position Refinement Algorithm

The initial estimation of the position of a node is refined by a distributed estimation algorithm. After a node computed an initial position estimation, it enters a refinement phase, where it refines iteratively the initial estimation via some algorithm until a stop condition is reached. According to [16], the Steepest Descent Algorithm is used to refine position estimations minimizing the error functional, that is the square of the difference between measured distance d (in the ranging phase) and estimated Euclidean distance $\hat{d}$ (based on the position estimation information):

$$F_i(n) = \sum_{j \in N(i)} [d_{i,j}(n) - \hat{d}_{ij}(n)]^2 \,,$$

$$x_i(n) = x_i(n-1) - \frac{1}{2}\mu \frac{\partial F_i(n)}{\partial x_i} \,,$$

$$y_i(n) = y_i(n-1) - \frac{1}{2}\mu \frac{\partial F_i(n)}{\partial y_i} \,,$$

where

$$\frac{\partial F_i(n)}{\partial x_i} = 2 \sum_{j \in N(i)} \frac{\hat{d}_{ij}(n) - d_{i,j}(n)}{\hat{d}_{ij}(n)} [x_i(n) - x_j(n)] \,,$$

$$\frac{\partial F_i(n)}{\partial y_i} = 2 \sum_{j \in N(i)} \frac{\hat{d}_{ij}(n) - d_{i,j}(n)}{\hat{d}_{ij}(n)} [y_i(n) - y_j(n)] \,.$$

$N(i)$ denotes the set of neighbors of node i. The pair $(x_i(n), y_i(n))$ denotes the position at time n, and μ is the so-called learning speed.

Due to the distributed nature of the algorithm, propagation of errors may occur and represent one of the major limitations. Therefore, the position estimation process and related broadcasting is scheduled by introducing a form of hierarchy that depends on the reliability level of the estimate. Let us assume that all nodes of a cluster are turned on at a given time and start the algorithm. The method relies on the following phases.

- In the first phase, only those nodes that perform cooperative ranging with, say, m anchor nodes start the (iterative) positioning algorithm and broadcast the related estimate at each step (*LABroadcast()*). After the broadcast estimates from other nodes are collected, the next refinement step starts (*LAStep()*);
- In the second phase, the positioning algorithm is started only by those nodes that perform cooperative ranging with at least m nodes, which are either anchors or nodes having already performed the first phase;
- A certain number of other phases can be scheduled; at each phase the positioning algorithm is started by those nodes that can perform cooperative ranging with m nodes, which are either anchors or nodes that have taken part to each previous phase.
- In the final phase all other nodes start their position algorithm. In this phase, an attempt is performed to solve eventual ambiguities for those nodes that do not have sufficient connectivity, by assuming cooperative decisions within the set of neighboring nodes (*LACoordination()*).

At each step, nodes update their accuracy level along with its position estimation. Anchors have an accuracy level set to 1, while sensor nodes start with a much lower level, e.g., 0.1. Accuracy level is computed only by sensor nodes, as follows:

$$al_i = \frac{1}{|N_i|} \sum_{j \in N(i)} (al_j - rp) \,,$$

where $|N(i)|$ is the number of valid neighbors. A neighbor j of node i is valid if $al_j > al_i$. That is: position estimation is performed only based on accurate information in order to mitigate the error propagation problem. Finally, rp is a ranging penalty, which accounts for errors in distance measurements.

B. Implementation of the Algorithm

To test the positioning algorithm, we built a localization module using TOSSIM [20], which is an environment that models also specific nodes' hardware details. By only replacing a few low-level TinyOS systems, this simulator can capture mote behavior at a very fine grain, allowing a wide range of experimentations. A TinyOS program is a graph of components representing independent computational entity. Components are composed by: commands, events and tasks. Command and events are mechanisms for inter-component concurrency. A command is typically a request to a component to perform some service, while an event signals the completion of that service. For a program to be well built, commands and events are required not to block: they must be highly responsive, thus returning immediately. Larger computations may be post to tasks, executed by the TinyOS scheduler at a later time.

Using TOSSIM for behavioral simulations is very important because it runs the same code that runs on sensor network hardware: by changing just a compilation option, a source code can be compiled for simulation on a PC instead of mote hardware, and vice versa. In our case we have developed a simulation model as sketched in Figure 5, where positioning algorithm is a task in the module *LocalizationM* and communication protocol is implemented using a sub module of the TinyOS standard (*RadioCRCPacket*).

We present here some preliminary positioning results of the implementation of the proposed refinement algorithm over a physical sensor network platform, composed by CrossBow's MICAz nodes [10], while an extensive analysis is in [16], [17] and [21].

In order to acquire distance measurements, in our test bed we used the Received Signal Strength Indicator (RSSI), which imposes a preliminary characterization of the propagation environment, by means of the estimation of two parameters:

- Parameter A: defined as the absolute value of the average power in dBm received at a close-in reference distance of one meter from the transmitter, assuming an omni-directional radiation pattern.
- Parameter a: defined as the path loss exponent that describes the rate at which the signal power decays

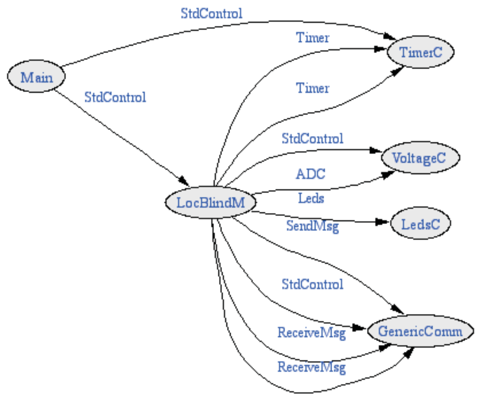

Fig. 5. A practical positioning implementation.

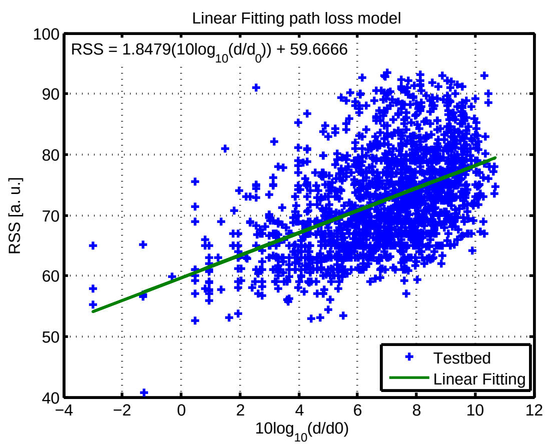

Fig. 6. Path Loss vs. log Distance.

with increasing distance from the transmitter. This decay is proportional to d^a where d is the distance between transmitter and receiver.

Parameters A and a can be estimated empirically [22] by collecting RSSI data (and therefore path loss data) for which the distances between the transmitting and receiving devices are known. RSSI measurements have been computed by deploying a number of MICAz nodes in a conference room located at our College of Engineering in L'Aquila, Italy. Figure 6 reports a scatter plot of abs(RSSI) data versus log distance in meters. A least-squares best-fit line is used to glean the specific values of A and a for the environment in which the data were measured:

- A is the y-intercept of the line, and
- a is the slope of the line.

Note that in the equation reported in Figure 6 we assumed $x = 10\log(d)$. Data in Figure 6 give $A = 59.6$ and $a = 1.84$ for that specific environment.

In the ventilation control scenario, we aim at locating a node in a room, by relying only to anchor nodes which can be placed at the room's entrance. However, it is interesting to formulate the problem in terms of locating nodes which cannot be surrounded by anchors. This leads to a Geometric Dilution Of Precision (GDOP) [23] of the positioning accuracy, that is a condition more prone to ambiguities. In order to take

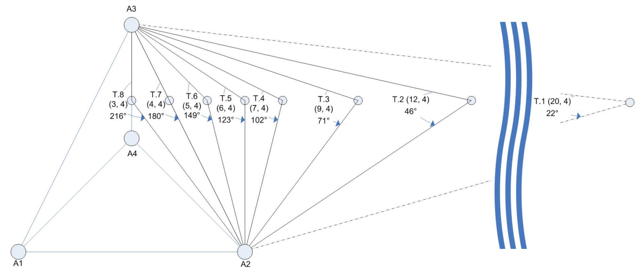

Fig. 7. Reference scenario (coordinates are expressed in 0.5m).

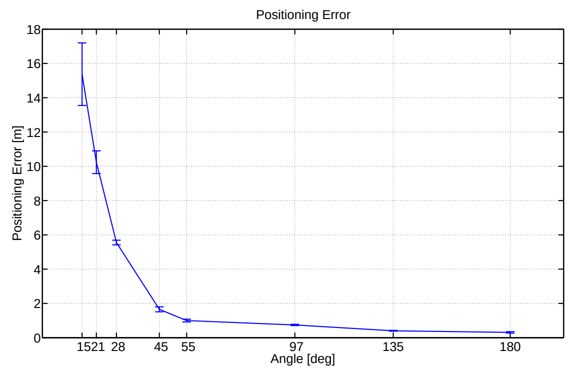

Fig. 8. Positioning error.

into account this problem, we set a reference scenario as that depicted in Figure 7.

We have three anchor nodes A1, A2 and A3, one non-coplanar anchor A4 and an unknown-position node U1, which may be located in one of the positions T_h with $h = 1, \ldots, 8$. To analyze the impact of the network geometry on the performance of the algorithm, in each position the unknown-position node sees the reference nodes with an increasing angle j when moving from T1 to T8: this corresponds to moving from a scenario (T1) with a bad geometry where ambiguities may arise during position estimation, towards a scenario (T8) where the unknown-position node is surrounded by reference nodes, thus giving ideally an optimal network topology for position estimation regardless of the specific algorithm [24].

The unknown-position node U1 has been placed in the positions T_h and runs several time the refinement algorithm described in Section A, resetting the algorithm each time the nodes changes position. Figure 8 shows the average positioning error h and its standard deviation σ with respect to the angle j. As a result, both h and σ increase as the angle j decreases. Depending on the application, a position quality threshold can be set, referred to the angle j, at the time of network deployment.

VI. Conclusions

In this work we reported on architecture definition and algorithms design for a wireless sensor network in the mining scenario. The work was carried out in the frame of the EC project HYCON, in close cooperation with the industrial partner ABB, which greatly stimulated the joint definition of a real test case. We outlined a complex network architecture, with the primary objective of supporting distributed estimation and fulfilling reliability and latency requirements imposed by a ventilation control application. Then, an enhanced architecture was proposed to support more advanced services in the mining context, namely, positioning and audio/video communications. A design flow was studied in more detail for a positioning service that relies on distributed and cooperative estimation. Models and simulation environments, that were specifically develop for the mining scenario, were described, along with the results of related experimental activities.

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