Heterogeneous Wireless Connectivity for Fixed and Mobile Sensing Applications in Industrial Environments

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Abstract

Improving the workers' health and safety should be a key priority in the design and development of the Factory of the Future concept. To this aim, ICT and wireless communication technologies in particular, can represent very valuable tools to implement distributed and mobile sensing applications capable to continuously sense the working environment and the workers' health and safety conditions. However, the harsh propagation conditions that can characterise industrial environments can difficult the efficient and reliable deployment of wireless solutions in factories. In this context, this paper evaluates the reliability and connectivity of heterogeneous wireless technologies that can be used for implementing fixed and mobile sensing applications.

1. Introduction

The European Factories of the Future (FoF) concept focuses on the development and integration of engineering technologies, ICT, and advanced materials for adaptable machines and industrial processes. In this new framework, workers represent an even more important asset for the manufacturing competitiveness and productivity, and all necessary actions must be done to improve their health and safety in their working environment. To this aim, the FASyS project (Absolutely Safe and Healthy Factory) [1] has been established under the Spanish CENIT initiative to develop a new factory model aimed at minimizing the risks to the worker's health and safety, and guarantee their welfare and comfort in machining, handling and assembly factories. To achieve its objectives, the project is addressing several aspects such as the development of prevention protocols and personalized health monitoring solutions, processing techniques of health data, and intelligence for analysis-decision, among others. A key technological component of FASyS is an end-to-end heterogeneous wireless network that will continuously sense the working environment and the workers' health and physiological conditions, both locally and remotely. The heterogeneous system will integrate short, medium and long range communication capabilities to provide the ubiquitous and potentially high bandwidth connectivity demands of a fully distributed safety monitoring solution efficiently operating in real-time.

The development of a heterogeneous wireless communications platform presents significant challenges. On one hand, industrial environments are usually characterised by challenging propagation conditions (obstructions, interferences, etc.) that difficult the establishment of robust wireless links. On the other hand, hybrid network architectures pose significant challenges to design a system platform efficiently managing data, in particular when real-time connectivity needs to be ensured across multiple wireless technologies. In addition, the capability to ubiquitously monitor the workers' conditions requires a mobile sensing and communications platform.

Prior to dimensioning and deploying a heterogeneous wireless solution, it is necessary to analyse the propagation, connectivity and Quality of Service conditions that the different technologies will experience in industrial environments. Different studies have already analyzed certain radio propagation aspects in industrial environments. For example, the work reported in [2] presents extensive narrow-band propagation measurements performed in five factories in the 1282MHz frequency band (with transmitting and receiving antenna heights of 2m). [3] extends the radio channel characterization in industrial environments to other frequency bands (900, 2400, and 5200MHz), and emulates what could correspond to a practical placement of industrial wireless access points and terminals (transmitting and receiving antenna heights of 6m and 2m). In [4], the authors evaluate the performance of an IEEE 802.15.4/ZigBee wireless sensor network consisting of 20 – 30 stationary nodes. The study concludes that reliability levels above 99.5% are possible. Other studies such as [5] and [6] evaluate the error rate and latency of IEEE 802.11 devices. All these studies prove it is possible to provide wireless connectivity in industrial environments, but also highlight certain peculiarities that need to be considered, and further issues that need yet to be analyzed. In addition, the studies reported to date are generally conducted with static nodes, whereas future mobile sensing applications will requires solutions to the challenges created by the mobility of nodes and the resulting varying propagation conditions. In this context, this paper presents the results of a measurement campaign that has evaluated the performance and connectivity levels of fixed and mobile IEEE 802.15.4/ZigBee sensing devices, as well as the quality of WiMAX and UMTS/HSDPA technologies that will be part of FASYS' heterogeneous platform.

2. Wireless industrial testing environment

The measurement campaign has been conducted in the main factory of GORATU, an important Spanish manufacturer of machine tools. Covering a surface area of more than 10.000m^2, the plant is characterized by a perimeter wall and a building height of around 11m (Figure 1). The interior of the plant mainly consists of wide corridors and large rooms typically separated by concrete walls of around 2m height that do not reach the ceiling. The corridors are machinery assembly areas, and tend to be occupied by large metal pieces. Each corridor and room has various large cranes that are able to lift and transport material of large weight (Figure 2). As illustrated in Figure 2, the plant is characterised by the presence of a large number of potential metallic obstacles that could influence the wireless connectivity.

The factory is located near 3 Base Stations (BS) that provide GSM and UMTS/HSDPA coverage to the city of Elgoibar. Figure 3 shows the location of the BSs and GORATU's factory. Although Elgoibar is located in a valley, surrounded by small hills, the factory has good visibility conditions with the BS located at less than 300m (BS1 in Figure 3).

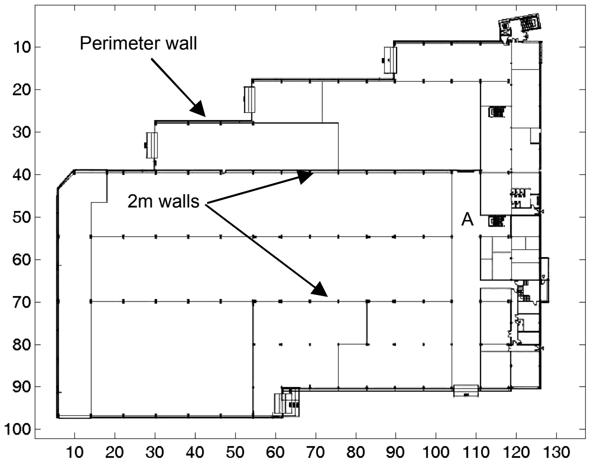

Figure 1. Plan of GORATU's main factory (axis in meters). A denotes the point from which the image shown in Figure 2 was taken.

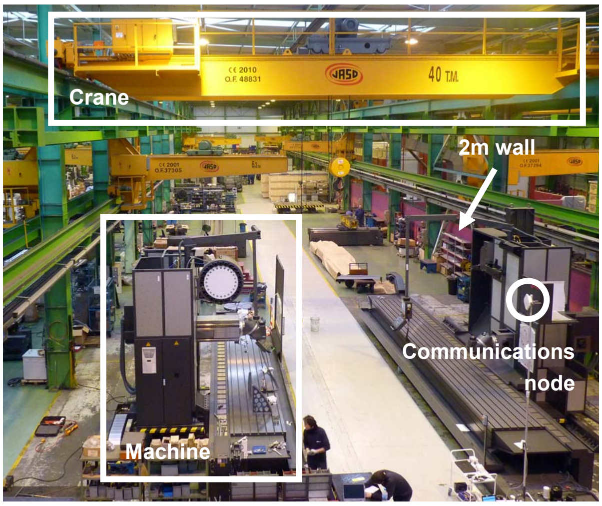

Figure 2. View of one of GORATU's corridors.

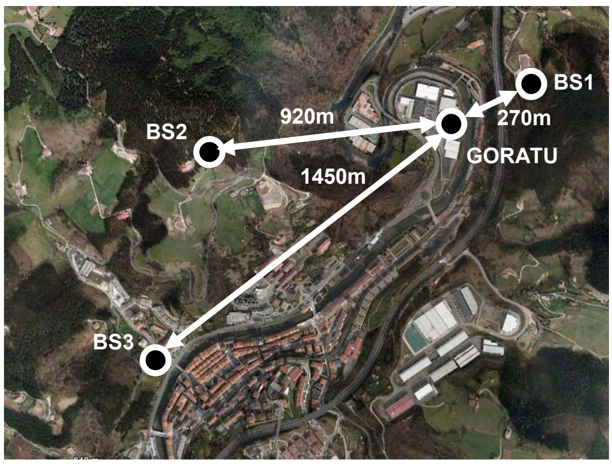

Figure 3. Cellular BSs close to GORATU's factory.

FASyS heterogeneous wireless communications platform is being designed to provide the capabilities to locally sense the physical environment and the workers' conditions, and transmit the sensed data to a control centre through a wireless backhaul. The wireless backhaul can include medium range technologies for communications within the factory, and long range technologies for the transfer of the aggregated data to the control centre. The local and real-time capability to monitor the physical environment and the workers' conditions requires the use of a cost-efficient and low power wireless technology that can adequately operate under low to medium mobility conditions. In this context, FASyS has adopted Wireless Sensor Networking (WSN) as its local mobile communications solution. The project is initially working with the IEEE 802.15.4/ZigBee standards, but is also planning to integrate WirelessHART and ISA100 technologies.

In addition to distributed sensing solutions based on 802.15.4/ZigBee, FASyS also includes video sensing applications that require higher communication bandwidths. In this context, FASyS proposes a hierarchical communications architecture where the wireless backhaul will integrate medium and long range communication technologies. The medium range technologies (WiFi and WiMAX) will be in charge of transmitting video data and locally sensed data from different areas of the factory (the local sensed data can be aggregated) towards the factory's gateway. This gateway will then be interconnected through long range communication technologies to a remote control centre. Depending on the final bandwidth requirements, FASyS is considering WiMAX and UMTS/HSDPA for connecting the factory's gateway towards the control centre.

3. Wireless sensor networking connectivity

3.1. Equipment setup

The experiments used two MEMSIC IRIS motes (transmitter and receiver) working in the 2.4GHz frequency band. The motes are characterised by a maximum data rate of 250kbps, a -101dBm receive sensitivity, and a maximum RF power of 3dBm. The IRIS motes implement the PHY and MAC layers defined in the IEEE 802.15.4 standard, and Zigbee compliant Network and upper layers. The motes include a processor board (XM2110) based on the Atmel ATmega1281 low-power microcontroller.

In the conducted experiments, the transmitter node is a MEMSIC IRIS mote powered by standard AAA batteries, and configured as a Zigbee router. This node runs an application that generates and transmits packets at a user-defined periodicity and payload, and can emulate either a fixed or mobile sensor node (e.g. carried by a worker using a belt or any vehicle moving in the plant). The receiver node is a mote configured as a Zigbee network coordinator, and connected to a PC through a MIB520CA Mote Interface Board. The application running in this node logs all received packets by forwarding them to the PC via USB (using a virtual COM port). In the PC, the received packets are tagged with a timestamp and logged. Additional information such as the received signal strength indicator (RSSI), link quality indicator (LQI), packet type, packet length and packet ID, is also logged for each received packet.

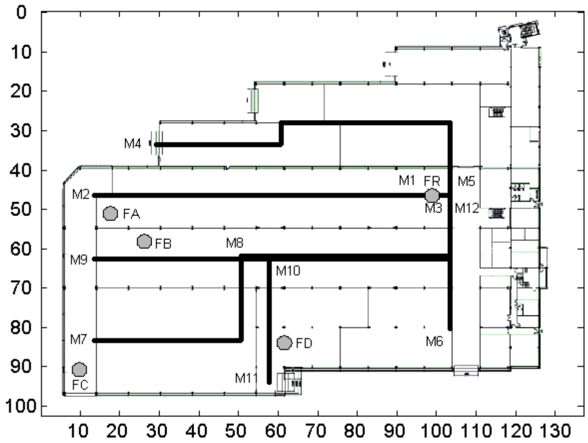

Figure 4. Position/trajectory of the IEEE 802.15.4/Zigbee transmitter node across GORATU's factory in the fixed and mobile experiments.

3.2. Experimental results

The receiver node was located at position *FR* (fixed receiver) in Figure 4, with an antenna height of h_R=5m. This node emulates a stationary node strategically deployed at a location with good propagation conditions with the different areas of the plant. With this antenna height, obstacles like short walls and metallic pieces/machines on the floor are partially avoided, although the cranes at different heights can still reduce the visibility conditions between transmitter and receiver. The IEEE 802.15.4/Zigbee performance was first analysed considering fixed transmitter nodes at different positions (*FA*, *FB*, *FC* and *FD* in Figure 4, *FD* is located within a warehouse) with an antenna height between 1.6m and 2m. The deployment emulates fixed wireless sensor nodes located at specific locations, e.g. machines that could represent a safety risk for the workers. In the experiments, the transmitter node periodically transmits at 3dBm a data packet every 20ms with 100Bytes payload. Figure 5 shows the RSSI levels measured at the four fixed positions. The highest received signal level is experienced at the *FA* location (at a distance of 85m from the receiver node) given the lower number of obstacles between the two nodes. The RSSI levels measured at positions *FB*, *FC* and *FD* (at a distance of 77m, 108m and 59m to the receiver node, respectively) do not significantly differ one from each other. The resulting packet error rate (PER) at the different locations was consistently below 3%.

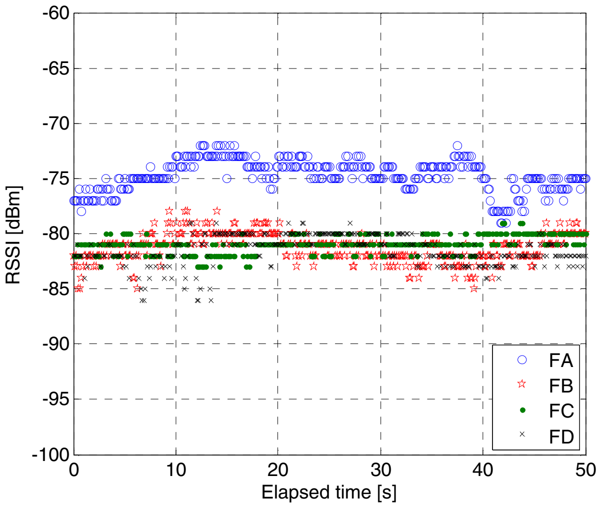

Figure 5. RSSI measured for the fixed IEEE 802.15.4/Zigbee experiments.

Different tests were also conducted to evaluate the wireless connectivity between a mobile node emulating a worker (or industrial vehicle) moving around the factory, and a fixed node emulating an access point. While the receiver node was located in *FR* with an antenna height of h_R=5m (see Figure 4), the transmitter node, with an antenna height of h_T=1.2m, moved across different areas of the plant at pedestrian speed. This node was also configured to periodically transmit a data packet every 20ms with a payload of 100bytes. Figure 4 shows the path followed by the transmitter node, starting in point *M1* (near the receiver node *FR*), then moving from point *M2* to point *M12* in ascending order. Figure 6 shows the RSSI levels measured during the mobile tests, together with the distance between transmitter and receiver. The signal level measured along the path presents variations between -45dBm and -91dBm (the minimum level that can be measured by the radio chip). In this context, it is interesting to note the high differences between the signal levels measured at the fixed positions and higher antenna heights (Figure 5), and the ones obtained under pedestrian mobility conditions and lower antenna height. In particular, the RSSI measured at the mobile points *Mi* (Figure 6) present higher attenuation and variability than the ones measured at the fixed points *Fi* (Figure 5). For example, RSSI values between -70dBm and -85dBm are observed at point *M2*, while the values observed at point *FA* range from -72dBm to -79dBm. Similar observations can be done when comparing the RSSI measured at *FB* with *M8-M9*, *FC* with *M7*, or *FD* with *M11*. These results provide a first insight into the link quality differences between fixed and mobile sensing nodes in industrial environments. The development of mobile sensing applications for improving the workers' health and safety would hence require a more careful design and dimensioning of the enabling wireless communications systems and protocols.

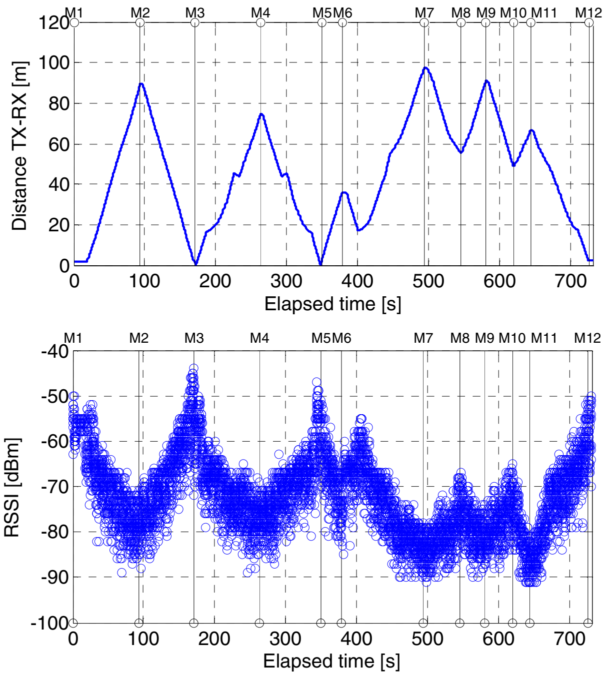

Figure 6. Distance TX-RX and RSSI measured in the mobile IEEE 802.15.4/Zigbee experiments.

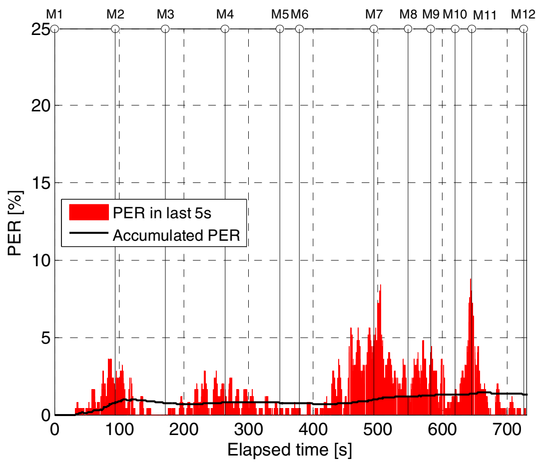

Figure 7. PER measured during the mobile IEEE 802.15.4/Zigbee experiments.

Figure 7 plots the Packet Error Rate (PER) measured during the mobile tests. In particular, the figure depicts the PER measured in the last 5 seconds, and the resulting accumulated PER. As it can be observed, relatively low PER values are obtained throughout the factory, being the farthest points the ones experiencing the worst performance (*M2, M4, M7, M9* and *M11*; *M11* is located within the warehouse). However, it is worth highlighting the PER differences measured during the fixed and mobile sensing tests. While only sporadic packets were lost with the fixed transmitting nodes, more than 8% of packets were received with error when the mobile nodes reached the *M7* and *M11* locations (positions close to *FC* and *FD*, respectively). These results demonstrate the challenges to be faced in order to efficiently and reliably deploy mobile sensing solutions in industrial environments, and the need to design advanced communications and networking techniques that overcome the degradation that has been observed under mobile conditions.

A possibility to improve the performance and reliability of data transmissions in mobile conditions is increasing the transmission power. The maximum power permitted in the 2.4GHz band for IEEE 802.15.4 channels is 17dBm. Such power level can be achieved with the selected motes using the CC2591 Texas Instruments power amplifier for the 2.4GHz band. With this power amplifier, the measured RSSI values were increased around 20dB in the mobile experiments. As a result, the PER was significantly improved. Figure 8 shows the PER measured by the mobile sensing node when moving from *M11* (warehouse) to *M12*, and using the power amplifier. As it can be observed, the PER is significantly reduced compared to Figure 7 thanks to the increase of the transmission power. However, despite a significant improvement of the RSSI, still some packets were received in error. In addition, increasing the transmission power significantly reduces the battery life, and impacts the nodes' autonomy. In this context, more advanced solutions would be more appropriate to address the communications challenges created by mobile sensing applications.

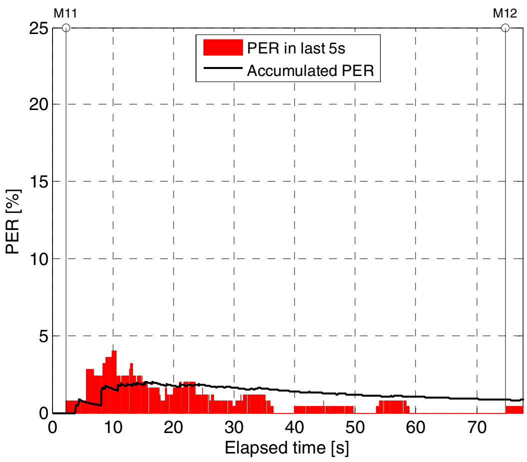

Figure 8. PER measured during the mobile IEEE 802.15.4/Zigbee experiments with higher transmission power.

4. Wireless communications for local data distribution

4.1. Equipment setup

In the conducted WiMAX experiments, Alvarion BreezeACCESS VL 5.4 units have been used. In particular, the Access Unit (AU) model AUS-E-SA-5.4-VL and the Subscriber Unit (SU) model SU-A-5.4-VL operating in the 5.470-5.725GHz frequency band were deployed at fixed locations in the factory. Each unit was connected to a standard laptop, and the AU was additionally connected to an external 120º sector antenna with 15dBi gain (model AL-484034/NV). Although these units were configured and used for point-to-point communications, they can also be employed for point-to-multipoint transmissions.

To evaluate the WiMAX performance, the Wireshark network packet analyzer has been used. This tool is able to capture the Ethernet traffic and filter it, and was used to capture the data packets received, and measure the throughput. Additionally, the Wireshark tool was used to capture the SNR (Signal to Noise Ratio), noise floor and RSSI acquired by the AlvariCraft tool. Using the AlvariCraft tool, these parameters are periodically transmitted from the AU to the laptop through the Ethernet interface using the SNMP protocol.

4.2. Experimental results

The WiMAX performance inside the factory has been evaluated through the transfer of a large file from the AU to the SU. The AU was located at point *A* in Figure 1 with an antenna height of h_T=6m. The SU was located at the largest distance possible from the AU, i.e. at point *FC* (Figure 4). To evaluate the impact of the visibility conditions and surrounding obstacles on the WiMAX performance, different SU antenna heights have been tested. The results plotted in Figure 9 show that with a h_R=5m SU antenna height, a sustained throughput of 37Mbps was obtained despite the presence of cranes and other obstacles between SU and AU that influence the radio propagation. The results depicted in Figure 9 also show that reducing the SU antenna height to h_R=1m decreases the average throughput to 12Mbps, and increases the link instability. These effects are due to the higher number of obstacles between the AU and SU (e.g. machinery) blocking the radio signal. In fact, the measured SNR decreased from 37.9dB to 24.7dB when the antenna height was reduced, and the average RSSI measured at the receiver also decreased from -47dBm to -60dBm. These results show that WiMAX can provide the high throughput levels in industrial environments that might be necessary for video transmissions, and the transmission of aggregated data from a large number of local sensors towards the factory's gateway to the control centre. In any case, it is important to emphasize that the performance levels heavily depend on an optimum deployment of the radio equipment to minimise the impact of surrounding obstacles. The impact of obstacles and the importance of an adequate deployment strategy are also observed when analysing the time between consecutive packet receptions (Figure 10). The measured results show that as the antenna height was reduced and the number of obstacles between SA and AU increased, the link stability was degraded, and the time between consecutive data packets increased.

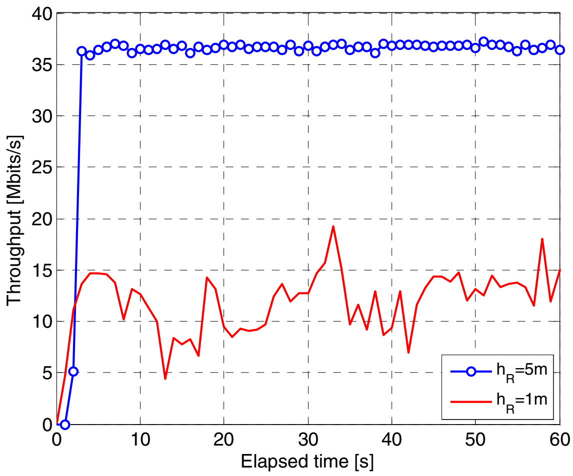

Figure 9. WiMAX application throughput.

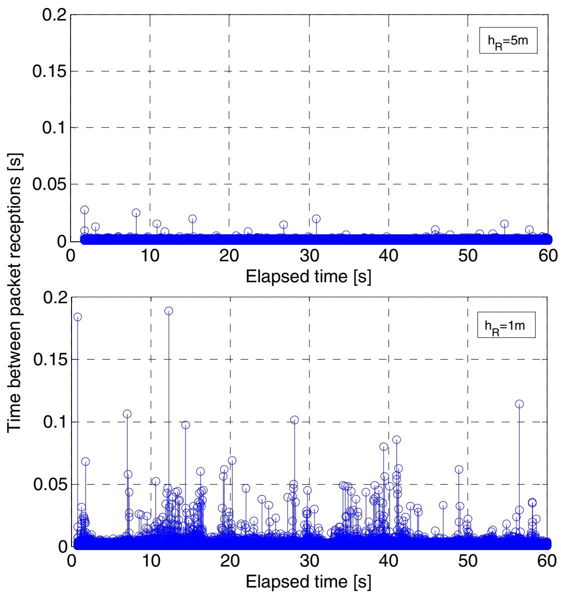

Figure 10. Time between consecutive packet receptions for WiMAX transmissions.

5. Wireless backhaul connectivity

5.1. Equipment setup

The UMTS/HSDPA communication capabilities have been measured using a Nokia 6720c handset. This Symbian-based terminal incorporates a portable engineering tool for measuring and monitoring the air interface of cellular technologies such as GSM/GPRS and UMTS/HSDPA. Nemo Handy collects extensive measurement results captured over voice and video calls, FTP/HTTP data transfers, HTML/WAP browsing and video streaming. The logged measured data has been processed using the professional Nemo Outdoor tool, which offers a valuable set of performance indicators such as throughput, BLER (Block Error Rate) or RSSI (Received Signal Strength Indication).

5.2. Experimental results

The UMTS/HSDPA performance has been evaluated through an HTTP data download of a large file. Figure 11 shows the RSSI experienced by the mobile node *outside* and *inside* the factory at fixed locations. The outdoor measurements were performed with the mobile terminal located on the roof of the factory, and the indoor ones were carried out in the corridor shown in Figure 2. The results plotted in Figure 11 show that the signal level is significantly reduced by the attenuation caused by the building itself and other obstacles inside the factory. In fact, the RSSI experienced inside the factory is 8dB lower in average than the level experienced on the roof, although the signal variability is slightly lower indoor (10.2dB vs. 8.8dB between the 5% and 95% percentiles).

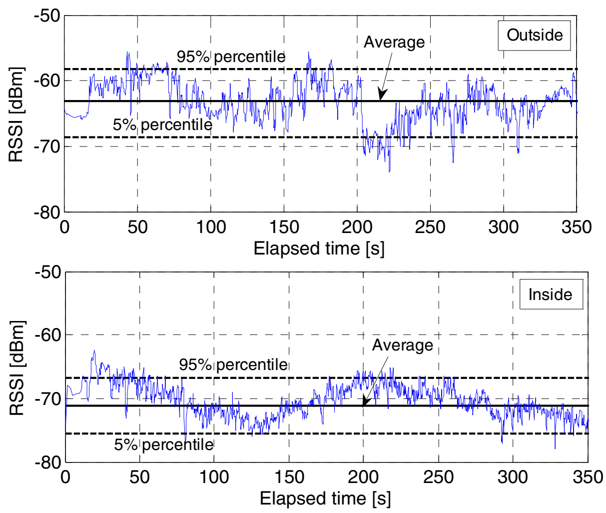

Figure 11. UMTS/HSDPA RSSI measurements for outdoor and indoor locations.

Figure 12 shows the instantaneous throughput levels experienced in the conducted experiments, together with the average, and the 5% and 95% percentiles. These results show that despite the RSSI degradation measured indoor, the system is capable to provide similar average throughput levels indoor and outdoor. To obtain similar throughput levels, the cellular technology adapted its transmission parameters (transmission power, modulation/coding scheme, etc.), and used its advanced radio resource management mechanisms to compensate the degraded indoor link quality conditions. In fact, the power level used by the terminal during the experiments was on average 8.55dB higher in the indoor test compared to the outdoor one. Moreover, to compensate the link quality degradation measured indoor, the cellular network had to assigned radio resources to the terminal during 91.25% of the time the indoor experiment lasted, whereas this percentage was reduced to 83.9% in the outdoor tests. These results show that cellular technologies can represent an attractive and viable solution to implement FASyS' wireless backhaul since it does not require the deployment of additional radio equipment, and its adaptive radio interfaces can efficiently adapt its operation to the experienced channel quality conditions in order to provide stable and relatively high throughput levels. An alternative to cellular systems for the wireless backhaul would be WiMAX that, as shown before, can provide very high throughput levels with an adequate deployment, although it requires a higher initial investment.

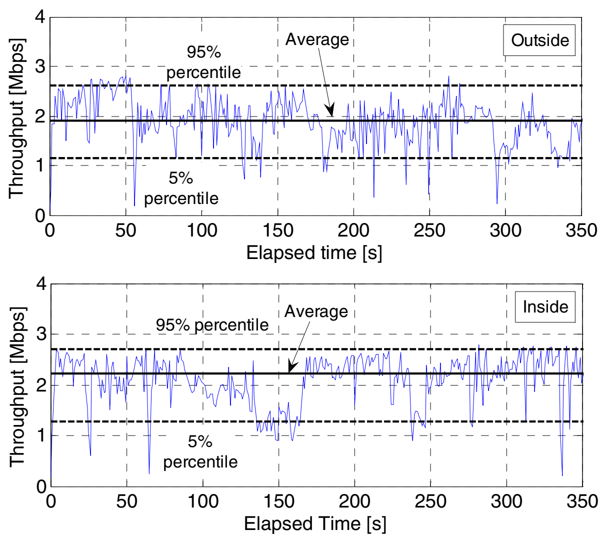

Figure 12. UMTS/HSDPA application throughput in indoor and outdoor experiments.

6. Conclusions

Distributed and mobile sensing technologies can offer interesting solutions to develop advanced industrial monitoring applications. In this context, the FASyS consortium is working on novel solutions to improve the workers' health and safety conditions through a heterogeneous wireless platform that integrates short, medium and long range communication technologies. While short range technologies will allow sensing functionalities, medium and long range technologies constitute the backbone for an efficient and scalable wireless backhaul solution that connects the physical environment to a remote control centre where safety conditions can be efficiently monitored to detect risky conditions, and identify the necessary countermeasures.

The deployment of wireless solutions in industrial environments is challenged by the potentially harsh radio propagation conditions that could degrade their transmission quality. In this context, this paper presents some results of an extensive measurement campaign conducted to analyse the capability of several wireless technologies to provide the connectivity and reliability levels required by FASyS to implement its safety and health applications. The obtained results reveal that IEEE 802.15.4/Zigbee, WiMAX and UMTS/HSDPA technologies could represent attractive and viable candidates. However, the conducted experiments have shown that mobile sensing applications in industrial environments require advanced communications and networking solutions to provide the real-time and reliable connectivity requirements that might be necessary for safety and health applications.

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