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On the feasibility to deploy mobile industrial applications using wireless communications

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ABSTRACT

Wireless communications can facilitate the deployment of novel industrial applications to improve productivity or health and safety conditions. Health and safety applications require mobile solutions capable to operate under harsh propagation conditions at low cost and energy consumption. This paper presents the results of an extensive measurement campaign that demonstrate the feasibility to deploy industrial mobile sensing applications with reliable wireless connectivity levels using short-range IEEE 802.15.4. The campaign also analyses the capability of various wireless technologies to provide the throughput levels necessary for wireless local data distribution and backhaul connectivity.

1. Introduction

Wireless communications are being gradually introduced in industrial environments to provide ubiquitous communication opportunities at reduced costs. Wireless solutions can also better adapt to changing operating and network environments than wired networks, and can offer better scalability and reconfigurability perspectives. The introduction of wireless communications in the factory of the future will also facilitate the deployment of distributed and mobile sensing applications for improving productivity levels and the workers' health and safety. In this context, the FASyS project (Absolutely Safe and Healthy Factory, http://www.fasys.es/en/) is investigating the design of an end-to-end heterogeneous wireless solution for continuously sensing the working environment and the workers' health and physiological conditions in order to be able to detect in advance any potential risks. FASyS exploits Wireless Sensor Networking (WSN) technologies (IEEE 802.15.4/ZigBee) to locally monitor the working environment and the workers' conditions. To transmit the sensed data to a control center, a wireless backhaul including medium range technologies for communications within the factory, and long range technologies for the transfer of the aggregated data to the control center has been designed. The medium range technologies (IEEE 802.11/WiFi and IEEE 802.16/WiMAX) transmit locally sensed data from different areas of the factory toward a gateway. The gateway can then transmit the received data using WiMAX and/or cellular to a remote control center. FASyS adopted a centralized approach in which a control center is in charge of controlling and supervising the sensors deployed and managing the heterogeneous wireless network. In particular, the control center manages the database of deployed nodes and sensor observations, and is also in charge of the real-time processing of all received information to trigger the necessary alarms when an unsafe or dangerous situation is detected. Additionally, the control center implements a toolbox that monitors the state of all wireless connections, and takes the necessary countermeasures to prevent link failures or congestions. While certain control functionalities can be distributed over different nodes, FASyS adopted a centralized approach so that the control center has a global view of the sensor network and can hence control the end-to-end Quality of Service (QoS). The adopted approach also facilitates a more scalable and cost-efficient deployment in the case of an industrial complex comprising several buildings or facilities. In this case, the different buildings will just require backhaul links to the control center. In Fig. 1, FASyS's industrial communications architecture is depicted.

Distributed communication systems in industrial environments are being evolved from the 1st generation of industrial networks, known as fieldbus systems and characterized by low bandwidths, to the 2nd generation using Real-Time Ethernet to reduce costs and increase data transfer speed [1]. Some of the most

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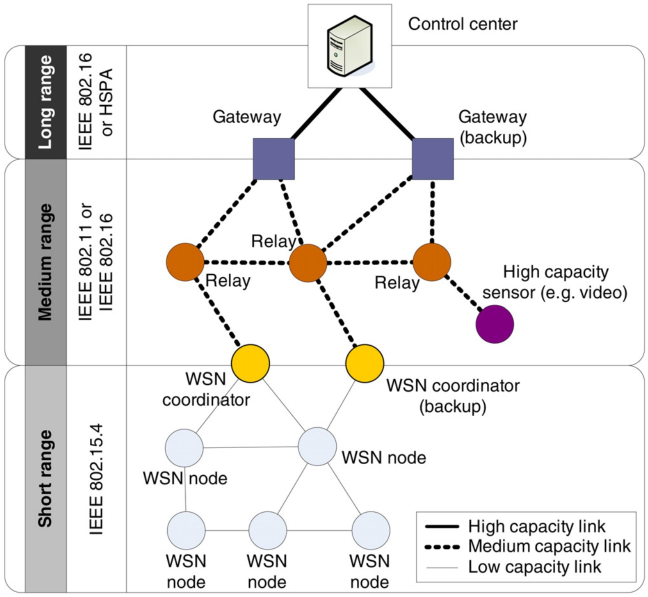

Fig. 1. FASyS's heterogeneous communications architecture.

significant challenges of distributed industrial communication systems include their integration with public IP-based networks for interconnecting remote subsystems [2], or standardization/interoperability issues [1]. In this context, several studies have highlighted the benefits of exploiting wireless communications technologies in general, and WSN in particular, in industrial communication distributed systems [1,3–7]. These benefits include deployment flexibility, low cost and reduced power consumption. However, the deployment of heterogeneous wireless communications in industrial environments presents significant challenges. On one hand, industrial environments are usually characterized by challenging propagation conditions (obstructions, multipath propagation, interferences, etc.) that difficult the establishment of robust wireless links. In addition, safety-related industrial applications are characterized by strict reliability and timing requirements, and therefore require a reliable mobile sensing and communications platform. In this context, this paper presents the results of a large field testing campaign that evaluated the communications performance of mobile IEEE 802.15.4 sensing communications, as well as the QoS that IEEE 802.11/WiFi, IEEE 802.16/WiMAX and HSDPA technologies can provide for backhaul connectivity. The campaign also included the deployment and testing of three use cases (collision avoidance, restricted access, and working at height) to highlight the safety-related potential of wireless industrial communications. The wireless traces obtained during the field testing campaign are openly released to the community to further facilitate research activities in wireless industrial communications. The traces can be downloaded from [8].

2. Related work

Different studies have analyzed wireless communications in industrial environments. They can be classified in three categories depending on their specific objectives and methodologies. A first group of studies focused on the characterization of the industrial radio propagation environment. A second category can be formed by studies that evaluate the achievable industrial communications performance using off-the shelf devices. Finally, the third category includes simulation-based and laboratory studies.

The studies focusing on the characterization of the industrial radio propagation environment typically analyze the received signal strength, amplitude probability distribution, *rms* (root mean square) delay spread, impulse response measurements, and coherence bandwidth. These parameters help understanding and characterizing propagation loses and distortions suffered by radio signals within factories. For example, the work in [9] has recently characterized three factory automation infrastructures at 439 MHz, 440 MHz, 570 MHz, and 2.45 GHz. The study revealed that the analyzed facilities have different levels of reflectivity, which can have a negative impact on the reliability of wireless technologies. Similarly, Tanghe et al. [10] reports a series of narrow-band measurements performed in two wood processing and two metal processing factories at three frequencies bands (900 MHz, 2.4 GHz, and 5.2 GHz). The study found limited path loss variations between measured factory buildings, mainly because of their similar constructional details. Temporal fading was found to be most significant in manual production lines, and to be overall less important than in office environments. The obtained measurements were later used to create a propagation model validated in [11] using IEEE 802.11 received signal strength measurements. An empirical propagation model was also presented in [12], where the wireless communications performance was characterized in a large industrial hall and four typical indoor office environments.

Other studies have evaluated the performance of wireless technologies in industrial environments, with many of these experiments based on the IEEE 802.15.4 and IEEE 802.11 standards due to their low cost and wide market acceptance [13]. For example, the work in [14] presents the results obtained in different field tests performed in various electric-power-system environments, including a 500-kV substation, an industrial power control room, and an underground network transformer vault using IEEE 802.15.4-compliant wireless sensor nodes. The obtained results (Packet Reception Ratio, background noise, channel characteristics, and attenuation) provide valuable information for the design and deployment of IEEE 802.15.4-compliant sensor networks for smart-grid applications. The study in [15] experimentally investigates the nature of IEEE 802.15.4-based packet transmission errors resulting from common stationary (e.g. machine shop) and moving obstacles (e.g. moving forklift) in small-scale manufacturing environments. The measurements show that transmission errors closely depend on the received signal strength, and could be mostly avoided by controlling the transmission power in order to ensure received signal strengths above the receiving sensitivity level. Other studies analyze the performance of IEEE 802.15.4 devices under particular industrial operating conditions. For example, the work in [16] experimentally evaluates the speed-dependent PER (packet error rate) of a rotating IEEE 802.15.4 device in a fast changing channel, which is typically experienced at a rotating mechanical structure. The study in [17] investigates the influence of the temperature on IEEE 802.15.4 communications in an outdoor WSN in an oil refinery, demonstrating that the temperature has an important effect on signal strength and link quality, and that operations at lower temperatures might require up to 16% less power to maintain reliable communications. Other experimental studies evaluating the performance of IEEE 802.15.4 and IEEE 802.11 devices in industrial environments can be found in [18–21]. These studies demonstrate that the physical layer of IEEE 802.15.4 can be suitable for industrial environments, and that reliability levels above 99% are possible under adequate node deployments. However, the studies also concluded that strong link quality variations can be found under frequently changing industrial environmental conditions.

The difficulties to conduct measurement campaigns in industrial environments have spurred many wireless industrial performance studies using simulation platforms [22] or off-the shelf devices in laboratory-controlled environments [23,24]. For example, Cena et al. [22] analyzes the performance that can be

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achieved in conventional QoS-enabled IEEE 802.11e networks when used to connect cell controllers and other intelligent devices in industrial environments. Bertocco et al. [23] analyzes the capability of IEEE 802.15.4 to support periodic and non-periodic traffic, typical of industrial applications, under the presence of interference. The obtained results revealed practical means to detect the occurrence of possible interference effects and optimize the network setup. The work in [24] evaluated the performance of an application layer protocol running over off-the-shelf IEEE 802.15.4 and IEEE 802.11 devices in a laboratory. The obtained results showed the influence of specific implementation aspects (implementation of communication standards, the application layer developed or software execution times) on the overall performance.

The reported studies coincide on the challenging industrial propagation conditions, the potential of wireless industrial communications, and the need to conduct additional studies to further understand how to optimally design and deploy future wireless industrial networks. In this context, this research aims to complement the existing studies with an extensive measurement campaign that, for the first time, evaluates the performance of wireless off-the-shelf devices for mobile sensing applications. The study is not limited to communications performance metrics, but also implements three significant safety-related industrial mobile applications. The obtained results provide important indications on the industrial wireless communications performance under mobile conditions. The main contributions of this study with respect to the state of the art are:

- Related studies only consider static nodes. On the other hand, this study conducts a comprehensive performance evaluation of IEEE 802.15.4 wireless industrial communications with mobile nodes.
- This paper also reports on the feasibility of IEEE 802.15.4 to support mobile industrial applications through the emulation of three safety-related use cases.
- The performance evaluation reported in this paper has been conducted using different IEEE 802.15.4 devices with diverse characteristics, and varying the operating and communications conditions (e.g. transmission power, data rate, antenna deployment height).
- Few studies have evaluated the performance of various wireless technologies under the same industrial environment. This study analyzes the performance of IEEE 802.11, IEEE 802.16/WiMAX, and HSDPA cellular for local data distribution within a factory, and wireless backhaul connectivity.

Field measurements are always tightly related to the specific testing environments. To derive general conclusions from the field measurements here reported, a challenging testing environment characterized by harsh propagation conditions has been selected. Selecting a challenging scenario allows checking the communications performance and the applications' effectiveness under worst case scenarios. If the performance targets are met, and the applications are shown to be feasible, then conclusions can be extended to scenarios characterized by more favorable conditions. In addition, measurements have been conducted under different operating and propagation conditions, and using various devices and technologies.

3. Industrial testing environment

The field testing campaign has been conducted in the main factory of GORATU, an important Spanish manufacturer of machine tools. Covering a surface area of more than 10,000 m^2, the factory has a perimeter wall and a building height of around 11 m. The interior of the plant is shown in Fig. 2, which mainly consists of wide corridors and large rooms typically separated by concrete walls of around 2 m height. The corridors are machinery assembly areas, and typically present large metal pieces whose spatial distribution at the time of conducting the measurement campaign is shown in Fig. 2. The receiver nodes are placed at fixed positions (*RXZ* and *RXW* in Fig. 2). On the other hand, the transmitter node is mobile, and moves around different areas of the factory characterized by varying operating and propagation conditions:

- LOS with reduced obstructions (Z1). Z1 is a corridor for machinery assembly of around 15 m × 100 m. As shown in

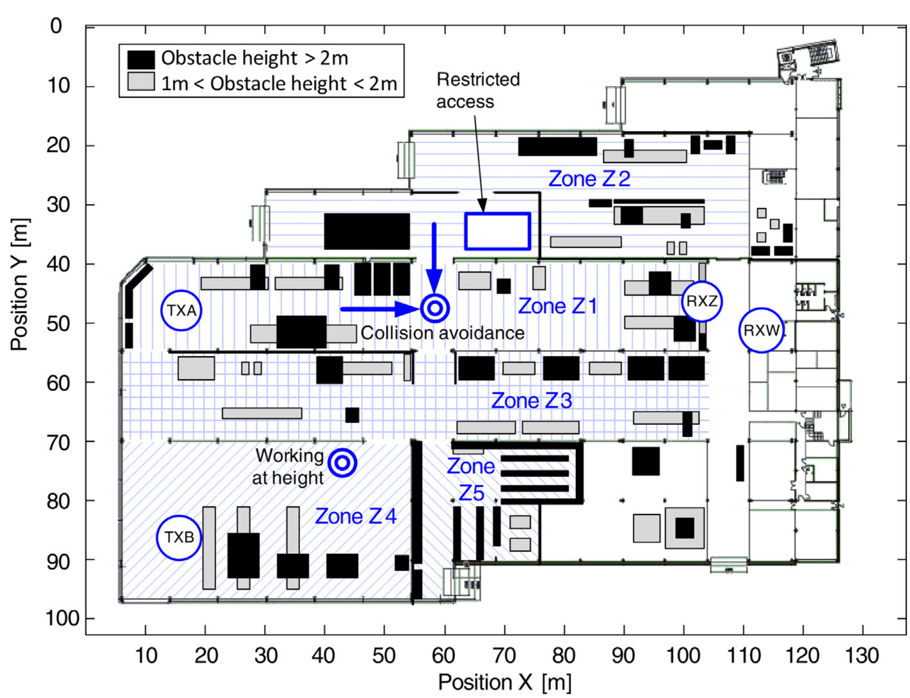

Fig. 2. Plan of GORATU's main factory (axis in meters).

Fig. 2, the center of the corridor remains free of obstacles, but it has large metal pieces/machines at both sides. The pieces are of different size, and their height varies between 1 m and 3 m. Z1 also has large cranes (at different heights) able to lift and transport material of large weight. Despite the presence of obstacles, LOS propagation conditions characterized the communications between a transmitter mote in Z1 and the receiver mote *RXZ* or *RXW*.

- Partial NLOS due to cranes, pillars, and machinery (Z2 and Z3). Z3 is a corridor for machine assembly of approximately 15 m × 100 m, similar to Z1, with the same type of cranes and large metal pieces/machines at both sides. Z3 and Z1 are separated by a concrete wall of around 2 m height. This wall, the pillars and cranes present in Z1 and Z3 reduced the visibility conditions between the receiver node in Z1 and the transmitter node located in Z3, thereby producing partial NLOS conditions in this area. Z2 is a machine assembly area with size of approximately 1300 m^2, and similar cranes and large obstacles. Z2 and Z1 are also separated by a concrete wall of around 2 m height, therefore producing also partial NLOS conditions in Z2.
- NLOS due to multiple obstructing elements and high distance (Z4). Z4 is a large machine assembly area of 45 m × 30 m, with large metal pieces of approximately the same size than in Z1, Z2 and Z3. Different cranes were also present in Z4. Z4 and Z3 are separated by a concrete wall of around 2 m height. The large distance between the receiver in Z1 and a node in Z4, together with the presence of two walls (the wall between Z4 and Z3, and the wall between Z3 and Z1), pillars and cranes, resulted in NLOS propagation conditions in Z4.
- NLOS due to heavy obstruction (Z5). Z5 corresponds to the factory's warehouse, an area of around 600 m^2 with a perimeter wall of 4 m height. Inside the warehouse, there are multiple corridors full of shelves with small metallic pieces. Due to its perimeter wall and multiple corridors, the propagation conditions between the mobile transmitter node in Z5 and the receiver mote in Z1 were classified as NLOS with heavy obstruction.

4. WSN mobile sensing connectivity

This section reports the IEEE 802.15.4 mobile connectivity measured at GORATU's factory using different radio motes characterized by different carrier frequencies, transmission power levels, and receiver sensitivities. The section also includes an analysis of varying communications settings and operating conditions on the mobile connectivity performance.

4.1. Testing equipment

Four different WSN motes were tested in GORATU to analyze the impact of various key communication parameters and receiver features. In particular, tests were conducted using devices operating at different frequency bands (2.4 GHz and 868 MHz), and with diverse transmission power and sensitivity levels. It is important noting that the FASyS project is working on novel mobile use cases and applications, wireless industrial communication protocols, and WSN-based indoor localization solutions. As a result, the energy consumption, possibility to use external antennas, and the access to a programmable protocol stack and accessible development environment, were also important factors to select the WSN motes to be tested. Table 1 summarizes the most significant technical characteristics of the tested WSN motes. The Memsic IRIS [25], Digi XBee-PRO ZB [26] and Microchip PICDEM Z [27] motes implement the standardized IEEE 802.15.4 PHY and MAC layers, and operate in the ISM 2.4 GHz frequency band using 5 MHz channels. On the other hand, Memsic's Mica2 mote [28] works in the ISM 868 MHz band using FSK modulation. The best receiver sensitivity is achieved by Memsic IRIS and Digi XBee-PRO ZB. The highest output power (and higher power consumption) is obtained with Digi XBee-PRO ZB, since it incorporates an internal power amplifier. Its transmission power is the maximum allowed by the standards in the ISM 2.4 GHz band for 5 MHz channels.

All the experiments used two motes (transmitter TX and receiver RX), where the TX mote was configured to periodically transmit 1-hop broadcast messages. An application running in the RX mote logs all received packets by forwarding them to a standard laptop via USB (using a virtual COM port). In the laptop, each received packet is 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. The RSSI parameter was available for all tested motes except for Digi XBee-PRO ZB. The LQI parameter was only accessible on a per-packet basis for Memsic IRIS and Microchip PICDEM Z.

The indoor position of the IEEE 802.15.4 motes was logged using Nemo Handy, an engineering tool used to monitor the performance and operation of cellular networks (see Section 6). In addition to its cellular monitoring capabilities, Nemo Handy allows geo-referencing the logged measurements. To this aim, a map of GORATU was loaded into Nemo Handy. The person carrying the mobile mote had then to manually introduce his position in Nemo Handy's indoor positioning module using the handset's keyboard. This approach provided sufficient positioning accuracy for our field measurements due to the controlled movement of the mote and its low speed.

It is important noting that the 2.4 GHz experiments avoided the use of frequency channels occupied by other technologies such as IEEE 802.11/WiFi. To this aim, the complete band was scanned with the FSH3 spectrum analyzer (Rohde & Schwaz) and WiFi analyzer tools (Chanalyzer MetaGeek), and a free channel was selected for the experiments. Readers interested on the coexistence between different technologies in the same frequency band can refer to [29].

4.2. Experimental results

The experiments reported in this section were conducted to analyze the connectivity between a TX mobile sensing mote (e.g. a mote attached to a worker or industrial vehicle) and a stationary RX coordinator. To this aim, the RX coordinator was deployed in a

Table 1
Selected IEEE 802.15.4 motes.

	Memsic IRIS	Memsic Mica2	Digi XBee-PRO ZB	Microchip PICDEM Z
PHY/MAC	IEEE 802.15.4 (DSSS/CSMA)	FSK/Manchester encoding	IEEE 802.15.4 (DSSS/CSMA)	IEEE 802.15.4 (DSSS/CSMA)
Frequency band	ISM 2.4 GHz	ISM 868 MHz	ISM 2.4 GHz	ISM 2.4 GHz
Transmit data rate	250 kbps	38.4 kbps	250 kbps	250 kbps
Max. RF power	3 dBm	5 dBm	18 dBm	0 dBm
Receive sensitivity	−101 dBm	−98 dBm	−102 dBm	−95 dBm
Current draw	16 mA (RX mode)	10 mA (RX mode)	47 mA (RX mode)	19 mA (RX, typical)
	17 mA (TX mode at 3 dBm)	27 mA (TX mode at 5 dBm)	205 mA (TX mode at 18 dBm)	23 mA (TX, typical)

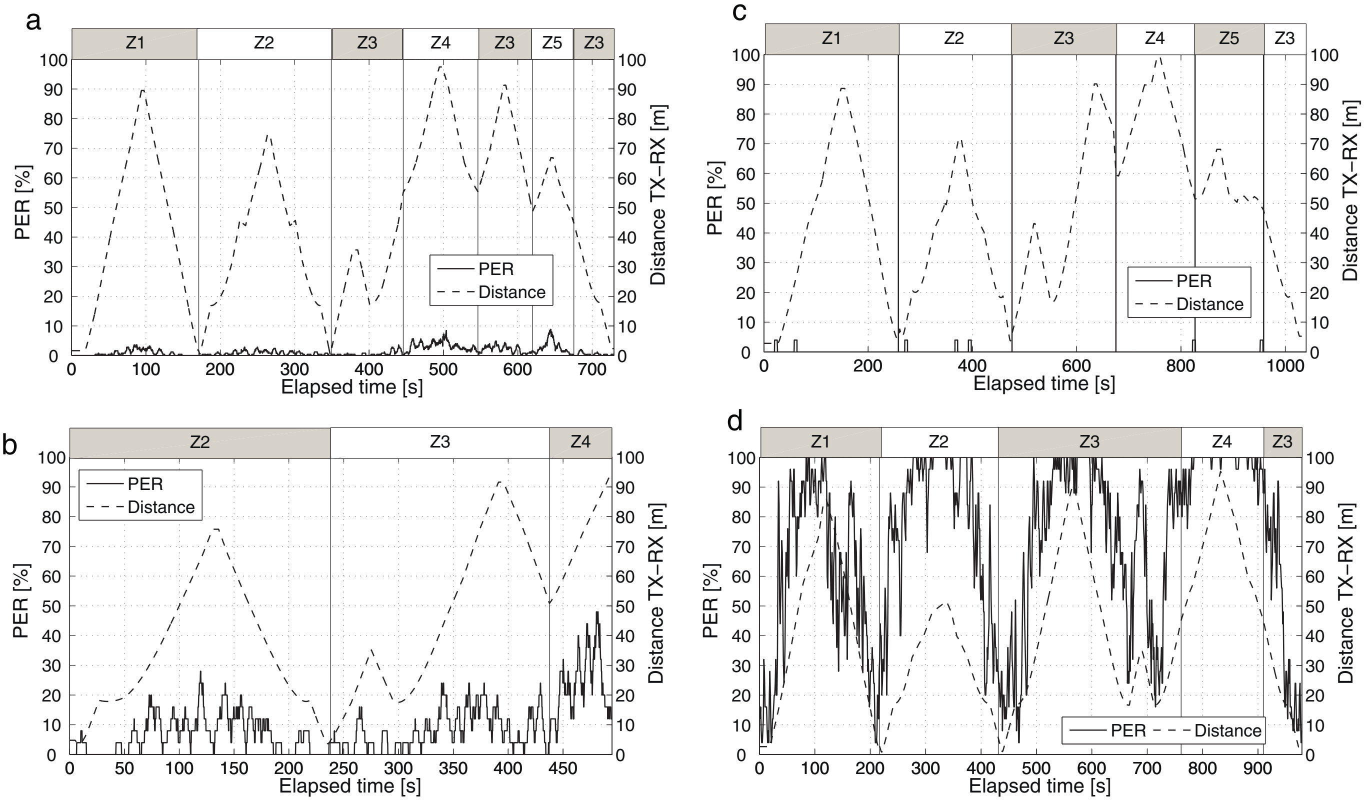

Fig. 3. PER performance as WSN motes move around the factory (h_{TX} = 1.2 m, h_{RX} = 5 m, T = 200 ms, payload = 50 bytes). (a) Memsic IRIS with Pt = 3 dBm. (b) Microchip PICDEM Z with Pt = 0 dBm. (c) Digi XBee-PRO ZB with Pt = 18 dBm. (d) Memsic Mica2 with Pt = 5 dBm.

location allowing the best possible conditions with the different areas of the factory (the RX coordinator was located at position *RXZ* in Fig. 2 with an antenna height of h_{RX} = 5 m). However, as described in Section III, LOS conditions were not possible with all areas of the factory. During the experiments, the TX mobile node (antenna height of h_{TX} = 1.2 m) moved across different areas of the factory at pedestrian speed. This node was configured to periodically transmit a data packet every T = 200 ms with a payload of 50 bytes excluding headers. Along its path, the TX mobile node experienced different propagation conditions, as detailed in section 3.

In Fig. 3, the PER levels measured with each of the four WSN motes as the mobile TX mote moves around the factory are depicted. The figure shows the average PER levels experienced during time intervals of T_p = 5 s, and the distance between the TX and RX nodes along the path. The figure differentiates the different zones of the factory. The results depicted in Fig. 3a show that reasonably good connectivity levels can be achieved throughout the factory with the Memsic IRIS mote, being Z4 and Z5 the zones presenting the worst performance. The medium transmission power level of this mote, together with its high sensitivity results in that the highest experienced PER level was around 8% in Z4 and Z5. These PER levels were achieved despite the fact that Z4 presents NLOS conditions due to multiple obstructing elements and high distance (more than 90 m), and Z5 presents NLOS conditions as a result of the transmitting mote being located within the warehouse at around 65 m. These results show the robustness of this mote under varied propagation conditions, and the feasibility to provide sustained wireless connectivity levels under mobile conditions. The relatively good performance levels obtained even under challenging propagation conditions in a factory emphasizes the validity of the DSSS (direct-sequence spread spectrum) PHY layer of the IEEE 802.15.4 standard under mobile conditions. This is in line with other studies [30,31] that highlighted under fixed conditions the potential of DSSS to support strong multipath distortions and handle harsh industrial environments. Given that sustained wireless connectivity levels can be achieved with the Memsic IRIS mote, additional measurements were conducted using the Microchip PICDEM Z mote (Fig. 3b). This mote is characterized by lower transmission power levels and a worse receiver sensitivity. The results depicted in Fig. 3b show that this mote significantly degrades the moble connectivity levels compared to the Memsic IRIS mote, and can significantly compromise the feasibility to deploy mobile applications under harsh industrial environments (e.g. Z4 and Z5). These results confirm the need to carefully select the devices to be deployed in industrial WSNs.

The results depicted in Fig. 3c show the performance obtained when using the Digi XBee-PRO ZB motes. These experiments were mainly conducted to analyze the effect of using higher transmission power levels. Although the results in Fig. 3c show that the PER is improved compared to the tests conducted with the Memsic IRIS motes, the improvements are not that significant considering the notably higher energy consumption of the Digi XBee-PRO ZB mote (shown in terms of current draw in Table 1). Given the importance of power consumption for mobile applications, the adoption of the Digi XBee-PRO ZB motes would depend on whether the Memsic IRIS motes are not capable to provide the PER levels required to support the industrial applications to be deployed. If this is not the case, the Memsic IRIS motes show a better performance/energy trade-off.

Lower carrier frequencies are usually characterized by lower propagation losses. This effect was evaluated with the Memsic Mica2 mote, and the results obtained are presented in Fig. 3d. It is important noting that it was not possible to find motes at 868 MHz with similar technical characteristics as the Memsic IRIS

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mote. The Mica2 mote was selected due to its low power consumption, the access it provides to the protocol stack and its adequate development environment (this was not always the case with other 868 MHz motes). The obtained results show that the use of a different receiver sensitivity level and transmission scheme at the PHY layer resulted in a notably lower communications performance. In fact, even under LOS propagation conditions in Z1 and short distances, the PER measured with the Memsic Mica2 mote reached high values.

The results depicted in Fig. 3 and the technical characteristics listed in Table 1 show that the Memsic IRIS mote exhibits the best performance/energy trade-off, and can sustain good mobile connectivity levels, even under harsh testing conditions. This device was thereby chosen for the remaining field tests. In particular, several field tests were conducted using the Memsic IRIS mote to analyze the influence of communication settings and operating conditions on the mobile connectivity performance. The following observations were made:

- Initial experiments were conducted with stationary TX and RX motes located at strategically selected locations, using $h_{TX} = 2$ m and $h_{RX} = 5$ m. In these experiments, the PER levels experienced were always below 3%, even when the TX mote was at large distances from the RX node and the propagation conditions were poor (Z4 and Z5). On the other hand, the results depicted in Fig. 3a show that the quality can be degraded (the PER was generally between 5 and 10% in Z4 and Z5) when the TX mote is mobile.
- Varying the RX antenna height (h_{RX}) can notably modify the propagation conditions between the nodes. In particular, reducing the RX height results in higher propagation losses at Z4 and Z5 due to an increase in the number of obstacles between nodes. Experiments were conducted reducing h_{RX} from 5 m to 2 m, and the measured PER levels as the RX mote moved around Z4 and Z5 increased from around 10% (Fig. 3a) to 20–22%.
- Experiments were also conducted with a mobile TX mote and varying the packet transmission period T (200 ms, 100 ms and 20 ms). In this case, no significant variations in PER levels were obtained compared to Fig. 3a. This trend could change in scenarios with multiple nodes transmitting over the same channel. In this case, reducing T would increase the channel load, and thereby the probability of packet collisions and higher PER levels.
- The effect of higher transmission power levels was first analyzed with the Digi XBee-PRO ZB mote. However, additional experiments were conducted with the Memsic IRIS mote and the CC2591 Texas Instruments power amplifier to observe the effect when using the same receiver. The power amplifier increases the transmission power level to around $Pt = 17$ dBm, which results in the PER being reduced from around 10% to less than 4% when the TX mote moved along Z4 and Z5. Despite the significant increase in terms of power transmission (and therefore energy consumption), the PER is still non negligible. These results show that instead of further increasing the transmission power, the use of more advanced receivers would be needed to further reduce the PER levels. In particular, IEEE 802.15.4 compliant motes using more sophisticated signal processing features (e.g. channel estimation and tracking) would be needed to further improve the communications performance.

The experiments reported in this section have focused on analyzing the reliability of mobile IEEE802.15.4 links. However, the obtained results can also be used to study the reliability at the application level by comparing the communications link reliability with the requirements of any application of interest, as it is shown in the next section through three safety-related use cases.

5. Safety related mobile sensing applications

The industrial FASyS partners have identified 54 industrial use cases with possible risks or dangers for the worker's health. Some of the identified use cases can strongly benefit from the use of wireless industrial communications. As a result, the field testing campaign also reproduced in real-time three of the use cases that can benefit most from the use of wireless industrial communications. In particular, the use cases reproduced at GORATU's factory are collision avoidance, restricted access, and working at height. The specific scenarios where these use cases were tested are characterized by some of the most challenging propagation conditions found at GORATU's factory. This approach was again chosen to ensure that the conclusions here obtained could be extended to other more favorable environments. The use cases were tested using the Memsic IRIS mote.

5.1. Collision avoidance

Collisions between workers and fork-lift trucks, or between any types of vehicles, have been identified as one of the most common accidents in factories. Such collisions could be prevented if workers and vehicles were equipped with WSN motes so that they could dynamically exchange in real time information about their position and speed. With this information, they could be able to detect in advance, and avoid, potential dangerous situations. To analyze whether robust and reliable wireless communication links can be established between any two mobile nodes with a risk of collision, this use case was reproduced in GORATU at the intersection highlighted in Fig. 2. This location was chosen due to its harsh propagation and visibility conditions caused by a wall, and large metallic machinery and obstructing elements placed within a large wood container at the intersection. One of the nodes was carried by a mobile worker (antenna height of $h_w = 1.2$ m), while the second node was placed on a fork-lift truck (antenna height of $h_f = 1.8$ m) traveling at a higher speed. Both nodes transmitted a data packet every $T = 200$ ms with a payload of 50 bytes excluding headers and $Pt = 3$ dBm transmission power. In Fig. 4, the RSSI is plotted for all received packets at both the mobile worker and the moving fork-lift truck. The figure shows that an increase of around 40 dB is experienced during the movement phase until the nodes reach the intersection or collision point; a large increase was observed when the nodes reach LOS propagation conditions. The experiment was repeated several times and the same trends were always observed. In this context, the collision between the worker and the fork-lift truck would be avoided if they are able to communicate at a distance to the intersection higher than the distance needed to decelerate and stop. This distance can be calculated with the following equation:

$$CD = v \cdot RT + \frac{1}{2}\frac{v^2}{a} \quad (1)$$

where $\boldsymbol{v}$ and a represent the fork-lift truck/worker speed and deceleration, respectively, and RT the reaction time of the driver/worker. Considering a fork-lift truck speed and deceleration of $\boldsymbol{v} = 3$ m/s and $a = 6$ m/s^2, respectively, and a driver's reaction time of $RT = 1.5$ s, the critical distance in the represented scenario was $CD = 5.25$ m for the fork-lift truck. As a result, the fork-lift truck should communicate with the worker before reaching such CD distance to the intersection to avoid their collision. The application's reliability can hence be evaluated through the analysis of the communications reliability at distances to the intersection larger than CD. Despite the bad visibility and propagation conditions between the two nodes in the NLOS area, all transmitted

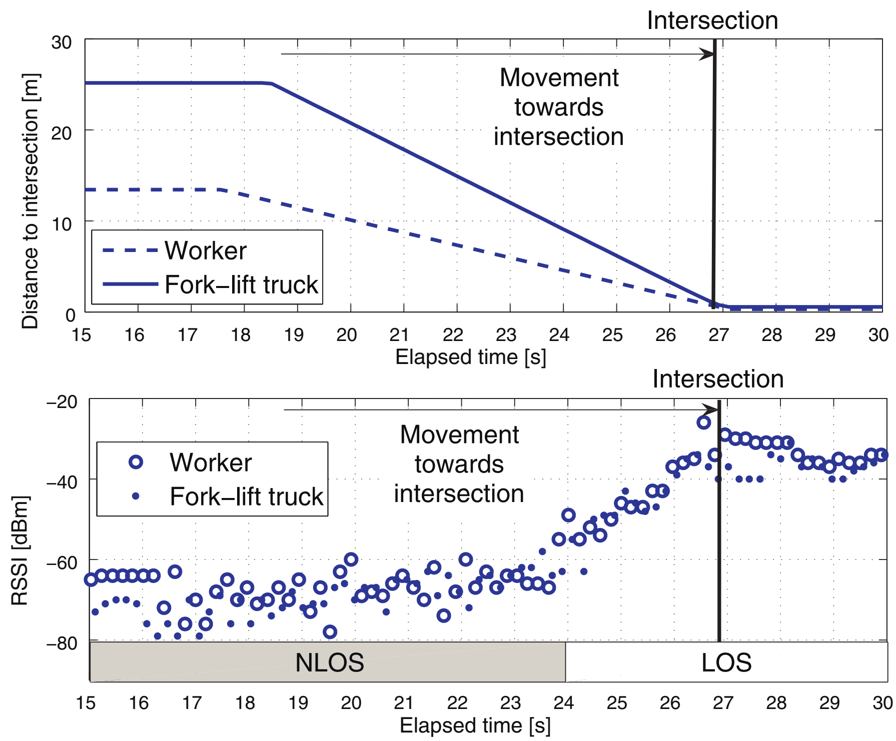

Fig. 4. Collision avoidance use case: distance to the intersection and RSSI of correctly received packets (Pt = 3 dBm, h_w = 1.2 m, h_f = 1.8 m, T = 200 ms, payload = 50 bytes).

packets were correctly received by the other node at distances to the intersection higher than 13 m for the worker and 26 m for the fork-lift truck. It was then possible to establish a reliable wireless connection between the two nodes at a distance higher than *CD*, i.e. with sufficient time for the driver/worker to react and avoid the collision. These results demonstrate the potential of wireless industrial communications to help reducing the risk of collisions.

5.2. Restricted access

Another identified risk is the access of workers to restricted areas with working machinery or where dangerous chemical products are used. In this case, the use of wireless communications could help control the workers' access to restricted areas. To this aim, the workers' would be equipped with a WSN mote that will

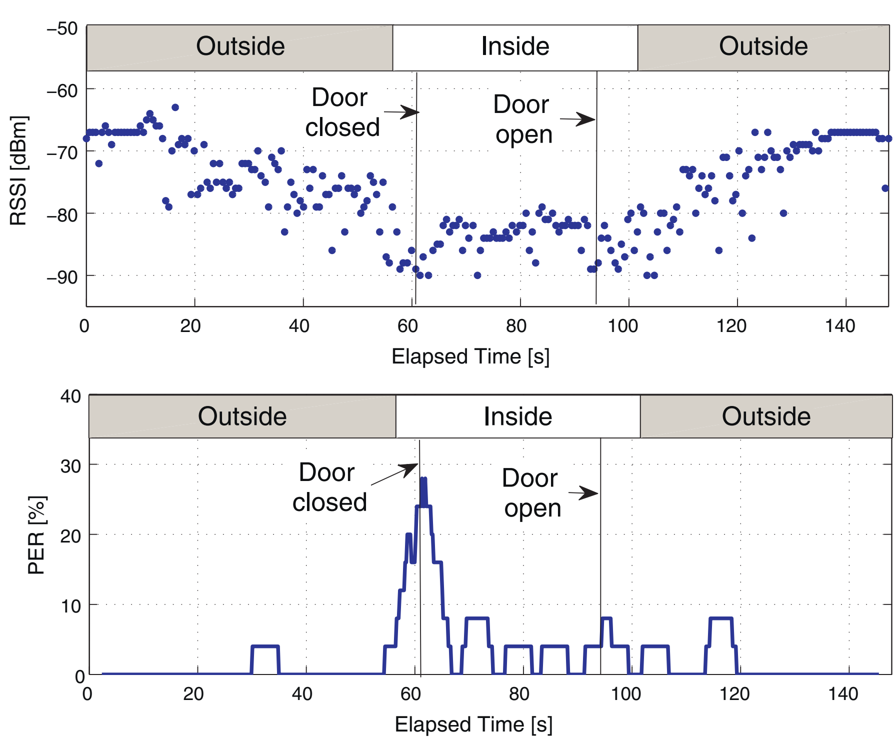

Fig. 5. Restricted access use case: RSSI of correctly received packets and PER (Pt = 3 dBm, h_{RX} = 1.5 m, h_{TX} = 2 m, T = 200 ms, payload = 50 bytes).

have to establish a reliable communications link with the control center to send his/her identification, current location, etc. and receive the appropriate permission from the system to access the restricted area. The wireless backhaul needed to connect the factory's gateway with the control center will be analyzed in Section 6; this section focuses on evaluating the link reliability between the workers' mote and a fixed WSN coordinator that would serve as gateway toward the control center. The coordinator is located at *RXZ* in Fig. 2 with a 2 m antenna height. Again, a data packet was transmitted every $T = 200$ ms with a payload of 50 bytes excluding headers and $Pt = 3$ dBm transmission power. This use case was reproduced in GORATU's factory using a painting booth as restricted area (the booth has an approximate size of 10 m^2, see Fig. 2). This scenario was chosen due to the adverse NLOS conditions when the worker enters the booth.

The RSSI and PER experienced when the worker entered the painting booth are shown in Fig. 5. The obtained results show that the RSSI is reduced around 20 dB when the worker goes into the booth. As it can be observed, the communications between the two nodes can still be maintained with acceptable PER levels as the worker enters the booth and experiences NLOS conditions. The obtained results also show that notable variations of the PER (reaching values between 20% and 30%) can be observed as the worker moves in and out of the booth. The time between correctly received packets (or update time) can serve as a metric to evaluate the application's reliability since it provides information related to the frequency with which the coordinator receives updated information from the worker. Despite the sporadic high PER levels shown in Fig. 5, the update time was below 0.39 s for 99% of the measurements. These experiments confirm that IEEE802.15.4 communications can provide the reliability levels needed for mobile sensing applications in harsh industrial environments.

5.3. Working at height

Activities at high altitudes represent an important risk if workers' do not use the necessary safety equipment. Wireless communications could help preventing falls from height by communicating to the control center whether a worker has activated her/his safety measures when working at height (the height could be estimated using barometers or inertial sensors) or not. Similarly to the previous use case, the worker's mote will need to establish a reliable wireless link to the WSN coordinator that will act as a gateway to the control center. To reproduce this use case, the worker's mote was attached to the top of a portable pneumatic telescopic mast (the location is depicted in Fig. 2). The mast, with minimum and maximum heights of 2 m and 10.5 m respectively, was progressively deployed and retracted during each experiment. Two different RX heights (2 m and 5 m) were tested for the fixed node emulating the WSN coordinator (*RXZ* in Fig. 2).

The RSSI and PER experienced during one of the experiments conducted for $h_{RX} = 2$ m are shown in Fig. 6. Each vertical line represents an increment/decrement of 1 m of the mast height during the deployment/retraction phases. The figure shows that relatively stable RSSI levels can be obtained when the TX node is stopped (i.e. when the mast is totally retracted or extended). However, high signal strength variations are observed during the deployment and retraction of the mast. Despite such high variations, PER levels above 10% were only experienced when the mast was totally extended. At this position, the TX node experienced the worst visibility conditions with the fixed node (partly due to the effect of cranes). These conditions can be improved by increasing the RX height to 5 m, although a high RSSI variability during deployment/retraction was also observed. Increasing the RX height improved the RSSI levels, e.g. an average RSSI of −75 dBm was experienced with the mast fully extended. The increased RSSI levels resulted in an improvement of the communications performance with PER levels below 10%. The analysis of the update time revealed that the time between correctly received packets was lower than 0.41 s and 0.375 s in 99% of the measurements for an RX height of 2 m and 5 m, respectively. As a result, independently of the deployment of the fixed RX node, the conducted experiments showed that IEEE 802.15.4 wireless

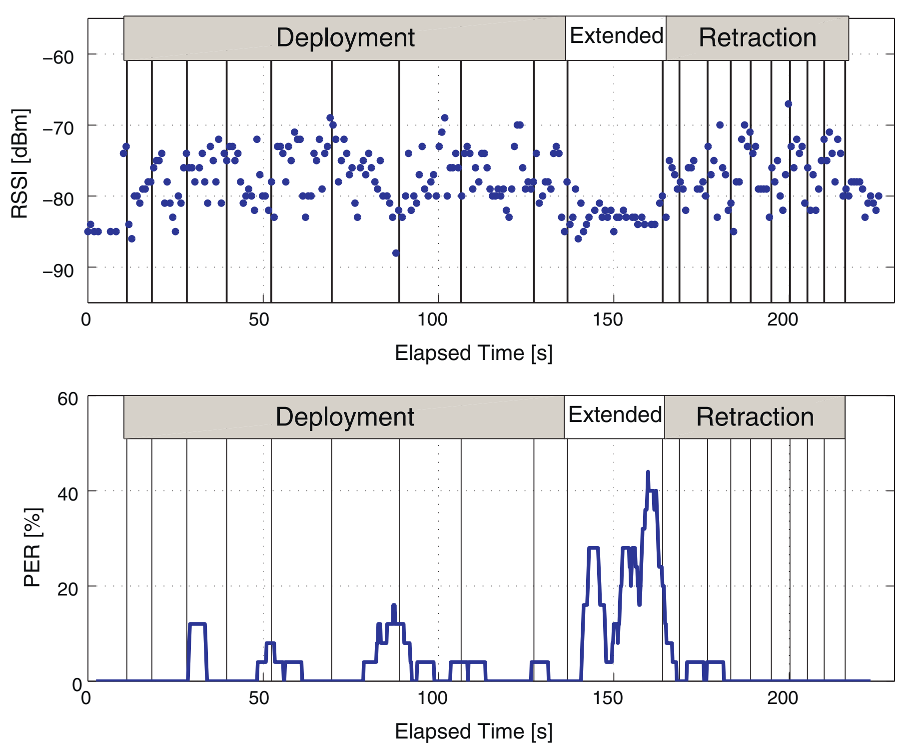

Fig. 6. Working at height use case: RSSI of correctly received packets and PER (Pt = 3 dBm, $h_{RX} = 2$ m, $h_{TX} = [2–10.5]$m, $T = 200$ ms, payload = 50 bytes).

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communications can provide the connectivity needed to communicate dangerous conditions when working at height.

6. Data distribution and backhaul connectivity

FASyS' architecture considers medium range technologies for communications and data distribution within the factory, and medium to long-range technologies for wireless backhaul connection. This section is aimed at analyzing the capability of various wireless technologies to provide data rates appropriate for industrial data distribution and backhaul connectivity.

6.1. Wireless local data distribution

IEEE 802.11/WiFi and IEEE 802.16/WiMAX have been evaluated as candidate technologies for local data distribution and the connection of distributed devices to the factory's gateway. The IEEE 802.11/WiFi experiments used standard laptops with built-in wireless interfaces and an additional external wireless interface to operate in ad-hoc mode under Linux. While the external wireless interface is in charge of the data packet transmission and reception, the laptop built-in wireless interface is in charge of monitoring the performance of the wireless links and measure the PER. The chosen external wireless interface is a wireless ExpressCard with Atheros chipset using the Linux Ath9k driver. Ath9k adapts the transmission power (maximum of 27 dBm) and data rate (maximum of 54 Mbps) to the link quality conditions. The Wireshark network packet analyzer has been used as a sniffer tool to capture IEEE 802.11 traffic through the laptop built-in wireless interface operating in monitor mode. During the experiments, two fixed nodes communicate with each other using 2.4 GHz IEEE 802.11 g, or IEEE 802.11a at 5 GHz. In each experiment, a large file is transferred using FTP. The RX node was located in *RXW* (Fig. 2) with $h_{RX} = 6$ m, while the TX node was located at *TXA* and *TXB* (Fig. 2) with $h_{TX} = 3$ m.

The link between RX and TX at *TXA* (85 m distance) is characterized by good propagation conditions, and serves as a reference for the performance evaluation of strategically deployed fixed wireless nodes under favorable conditions. On the other hand, the link between RX and TX at *TXB* (100 m distance) presents NLOS conditions due to multiple obstacles between the nodes (see Section 3). While practical fixed deployments would seek positions with favorable conditions for reliable and stable data distribution in the factory, the performance evaluation at *TXB* provides indications about the capability of IEEE 802.11 to operate under possible adverse conditions if favorable deployments are not possible. The conducted experiments resulted in an average RSSI level at *TXB* 9.3 dB lower than at *TXA* with 2.4 GHz IEEE 802.11 g. *TXB* was also characterized by relatively high PER levels due to poorer propagation conditions (the average PER increased around 12.8% in *TXB* with respect to *TXA*). The higher PER levels observed with respect to IEEE 802.15.4 (e.g. Fig. 3a) could be due to the Ath9k rate-control algorithm, which is designed to favor higher data rates instead of transmitting a packet with the minimum number of attempts (it hence favors the use of less robust modulation and coding schemes). The link quality differences observed at the two transmitter locations result in significant application throughput variations (Fig. 7). While a 7.1 Mbps average throughput was measured at *TXA*, the performance at *TXB* was reduced to 1.1 Mbps.

The use of the higher 5 GHz band for IEEE 802.11a, which is typically less congested than the 2.4 GHz band, resulted in higher propagation loses, lower RSSI and higher PER. In fact, the average RSSI level at *TXA* and *TXB* was reduced by 9.3 dB and 5.8 dB respectively compared to IEEE 802.11 g at 2.4 GHz. The average PER increased by 10.7% and 2.9% at *TXA* and *TXB*. The reduced IEEE 802.11a link level performance resulted in a lower application throughput (1.37 Mbps and 0.83 Mbps at *TXA* and *TXB*) and a higher time between correctly received packets (update time). As a result, the possible IEEE 802.11a congestion benefits are significantly reduced due to the lower resilience to propagation loses.

The conducted IEEE 802.11 experiments have shown that the provision of high throughput levels in industrial environments requires good deployment conditions and the use of low frequency bands. However, video applications or large-scale deployment of WSN nodes might require higher throughput levels than those provided by IEEE 802.11. Additionally, LOS conditions might not

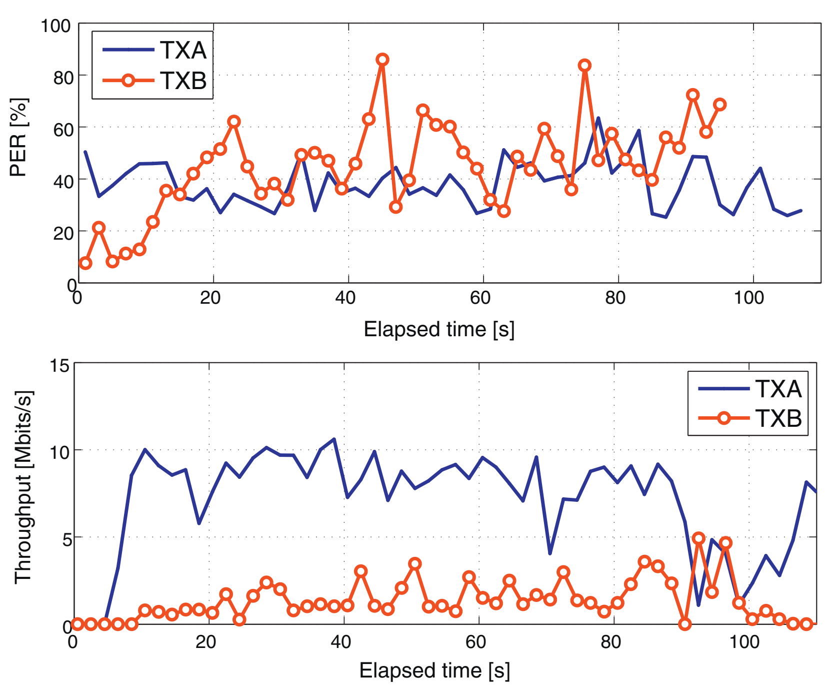

Fig. 7. PER and application throughput in the IEEE 802.11 g experiments at 2.4 GHz.

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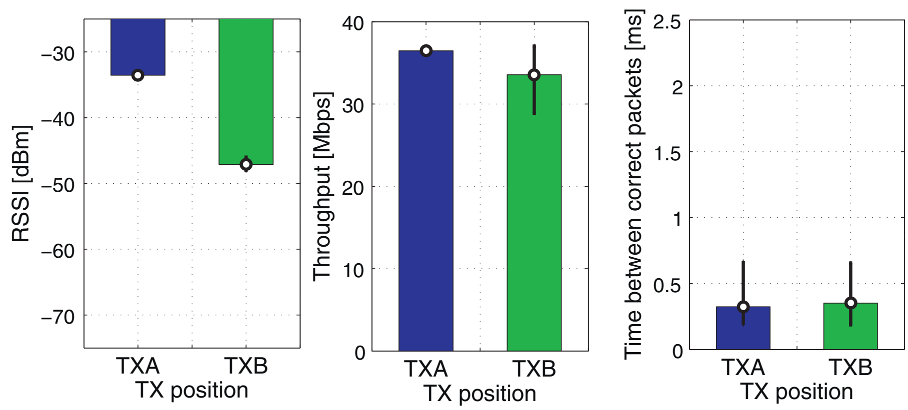

Fig. 8. IEEE 802.16 performance at two different positions (TXA and TXB) with h_{TX} = 5 m, h_{RX} = 6 m and Pt = 30 dBm. The bars represent the average values, and the lines represent the intervals for 5% and 95% percentiles of the RSSI, throughput and time between correctly received packets.

always be feasible, and more robust wireless technologies might be needed. In this context, additional IEEE 802.16/WiMAX experiments were conducted using Alvarion BreezeACCESS VL 5.4 units deployed at fixed locations (Access Unit model AUS-E-SA-5.4-VL and Subscriber Unit model SU-A-5.4-VL). The Access Unit was connected to an external 120° sector antenna with 15 dBi gain (model AL-484034/NV). The units operate in the 5.470–5.725 GHz frequency band, and can provide a maximum output transmission power of 30 dBm and a theoretical maximum bit rate of 54 Mbps (the data rate is dynamically adapted based on the link quality). The units were configured for point-to-point communications using 20 MHz channels. Transmitted and received packets were also captured using the Wireshark network packet analyzer. Two WiMAX nodes were deployed, and a large file was transferred using FTP. The RX node was located at *RXW* with h_{RX} = 6 m, and the TX node was located at *TXA* and *TXB* (Fig. 2) with different TX heights and transmission power. Fig. 8 shows that the worse propagation conditions with the receiver at *TXB* results in a 13 dB average RSSI reduction, and a lower application throughput (from 36.5 Mbps at *TXA* to 33.5 Mbps at *TXB*). The throughput experienced at *TXA* is close to the levels obtained under good conditions in laboratory-controlled environments. Reducing the transmission power from 30 dBm to 20 dBm reduced by 10 dB the average RSSI at *TXB*, and the average application throughput decreased from 33.5 Mbps to 22.4 Mbps. A similar effect was observed when using 30 dBm transmission power but reducing the antenna height at *TXB* from h_{TX} = 5 m to h_{TX} = 1 m. In this case, the worse propagation conditions decreased the average RSSI level by 12.8 dB, and reduced the application throughput from 33.5 Mbps to 12.4 Mbps. The reasonably good performance observed in *TXB* under NLOS conditions and adverse configuration options (low transmission power and antenna height) shows that IEEE 802.16/WiMAX can better overcome adverse industrial propagation conditions for wireless local data distribution than IEEE 802.11.

6.2. Wireless backhaul connectivity

IEEE 802.16/WiMAX can also be considered for wireless backhaul connectivity between a factory and a remote control center since it represents a cost effective solution due to the use of ISM frequency bands. However, it can require the use of relaying nodes in the case of important obstructions (e.g. buildings) between the transmitter and receiver. This was actually the case when trying to connect GORATU's main factory (*Lerun*) and a second building (*Urasandi*), located at approximately 700 m that emulated a remote control center. A small hill between the two buildings prevented the establishment of a direct WiMAX communications link. Instead, an intermediate relay WiMAX node located on top of a nearby hill was needed to communicate the two buildings. In this case, the measurements conducted showed high performance levels: average RSSI levels above −55 dBm, average application throughput values of more than 33 Mbps, and update times below 0.5 ms (time between correctly received packets). These throughput levels were considered by the FASyS partners to be sufficient to sustain safety-related wireless backhaul needs.

Additional wireless backhaul measurements were conducted using HSDPA cellular technology. However, indoor and outdoor application throughput levels did not surpass 2.5 Mbps, which could be insufficient for certain wireless backhaul deployments, especially those requiring the transmission of video or images, cellular systems could provide a more stable operating environment. The trade-off between the cost of deploying wireless relay nodes and the cost of cellular transmissions is another aspect to be considered. It is important noting that the cellular throughput levels are significantly influenced by the cellular standard capabilities, specific configuration and technologies deployed at each base station, and the cell load.

7. Conclusions

The use of heterogeneous wireless solutions in industrial environments could facilitate the deployment of applications to improve productivity levels as well as the workers' health and safety. Some of these applications might require mobile solutions, and the capability to operate under harsh radio propagation conditions. In this context, this study presents the results of an extensive field testing campaign in industrial environments that demonstrates for the first time the feasibility to deploy industrial mobile sensing applications with reliable wireless connectivity levels using short-range IEEE 802.15.4 technologies. To this aim, several relevant safety-related mobile applications have been deployed, and the wireless communications performance has been analyzed under different conditions and scenarios. The wireless connectivity necessary to sustain mobile applications has been shown to significantly depend on the transceiver used, and the location and deployment conditions. Additional measurements have demonstrated the possibility to deploy heterogeneous wireless solutions for local data distribution, and connection of distributed devices to the control center through factory gateways. In particular, the conducted measurements have shown the benefit of using lower frequency bands for IEEE 802.11 technologies, and the capability of IEEE 802.16/WiMAX to better handle adverse indoor deployment scenarios. The wireless traces obtained during the field testing campaign are openly released to the community to further facilitate research activities in wireless industrial communications [8].

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