Wireless Connectivity for Mobile Sensing Applications in Industrial Environments

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Abstract — **The future deployment of distributed and mobile sensing technologies in industrial environments provides interesting opportunities to further improve the workers' health and safety in the Factories of the Future. Such technologies will allow detecting in advance dangerous situations and conditions, and taking the necessary preventive actions. Wireless technologies would represent an essential component of the Factories of the Future in order to facilitate the real-time and ubiquitous connectivity of mobile sensors. In this context, this paper presents initial results of a measurement campaign that analyses the connectivity capabilities of the IEEE 802.15.4/ZigBee technologies for mobile sensing applications, and their use in collision avoidance applications.**

Keywords – wireless connectivity; mobile sensing; industrial environment; hardware testbed; radio propagation

I. INTRODUCTION

Different international research initiatives are currently working towards the definition and design of the Factories of the Future (FoF) concept. At the European level, the FoF initiative concentrates on increasing the technological base of European manufacturing, with a particular focus on the development and integration of enabling technologies, such as engineering technologies, ICT, and advanced materials for adaptable machines and industrial processes. In this new FoF framework, the workers and their know-how will 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], grouping a unique consortium of 13 companies and 14 research institutions, 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, e.g. the development of prevention protocols and personalized health monitoring solutions, processing techniques of health data and intelligence for analysis-decision, etc. A key technological component of FASyS is an end-to-end heterogeneous wireless system that will be designed to allow for the continuous sensing of the working environment and the workers' health and physiological conditions, both locally and remotely. Such system is being designed to be able to detect in real-time potential dangerous conditions, and launch the necessary countermeasures to prevent their impact on the workers' health and safety. One of the technologies that will be part of the heterogeneous FASyS solution due to its flexibility, low cost and power consumption is Wireless Sensor Networking (WSN).

WSNs offer the possibility to support distributed mobile sensing applications in a variety of environments. However, their use in industrial environments, typically characterized by active machinery and the presence of highly reflective materials (e.g. metal), requires a careful analysis of the propagation and connectivity conditions before dimensioning the network to be deployed. Different studies have analyzed and characterized the radio propagation conditions in the industrial environment. For example, [2] reports on extensive narrow-band propagation measurements performed in five factories in the 1282MHz frequency band; the measurements were conducted considering a 2m transmitting and receiving antenna height. Based on the obtained results, the authors classify the physical characteristics of the radio channel in 4 categories depending on the factory topography, taking into account aspects such as the visibility conditions (LOS, Line of Sight) and surrounding obstacles. [3] extends the radio channel characterization in industrial environments to other frequency bands (900, 2400, and 5200MHz). The study was based on an antenna deployment emulating what could represent a practical placement of industrial wireless access points (antenna height of 6m) and terminals (antenna height of 2m). This model was later validated in [4] with measurements of the received signal strength reported by WLAN monitoring software. Studies such as [5] or [6] analyze in detail the physical effects of reflection, diffraction and absorption produced by certain obstacles at different distances of the wireless node. These studies highlight the high influence of the position of transmitter and receiver nodes with respect to metallic surfaces due to the strong signal reflection. In [7], the author evaluates the performance of an

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IEEE 802.15.4/ZigBee WSN consisting of 20 – 30 stationary nodes. The obtained results show that reliability levels above 99.5% are possible if the nodes are properly placed. A related study including also estimates of the packet error rate and latency has been presented in [8] using IEEE 802.11 devices. The reported studies to date are generally conducted with static nodes and relatively high antenna heights. The potential and demand for mobile sensing applications in industrial environments, for example to improve health and safety, requires further studies considering mobility of nodes and low antenna heights to emulate sensors monitoring the workers' conditions. In this context, this paper presents the initial results of a measurement campaign conducted to evaluate the wireless connectivity of IEEE 802.15.4/ZigBee mobile sensing devices in industrial environments.

II. 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. 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 affect the wireless connectivity.

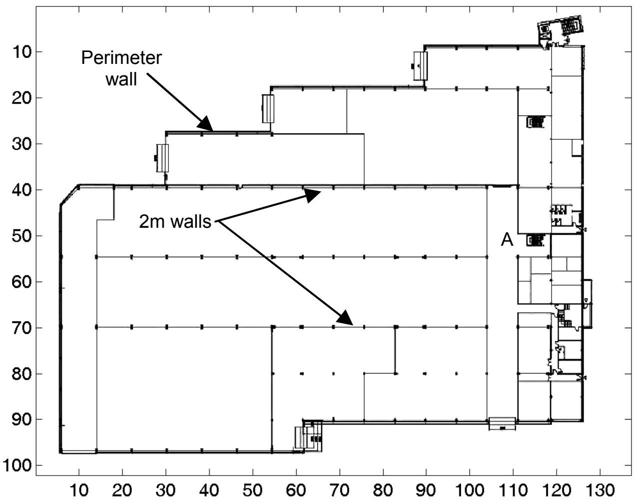

Figure 1. Plan of GORATU's main factory (axis in meters). *A* denotes the point from which the image shown in Figure 2 was taken.

The measurement campaign results reported in this paper were obtained using two MEMSIC IRIS motes [9] (transmitter and receiver) working in the 2.4GHz frequency band. The motes can transmit at a maximum data rate of 250kbps, and a 3dBm RF power. In addition, they are characterised by a -101dBm receive sensitivity. The IRIS motes implement the PHY and MAC layers defined in the IEEE 802.15.4 standard, and the Network and upper layers used are Zigbee compliant.

In the conducted experiments, the transmitter node is a moving MEMSIC IRIS mote powered by standard 2xAA 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 emulates a node carried by a worker (e.g. using a belt) or any vehicle moving in the plant. The receiver node is a MEMSIC IRIS 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. Coexistence aspects have not been dealt in this paper, and the tests avoided using channels occupied by other wireless systems such as IEEE 802.11/WiFi.

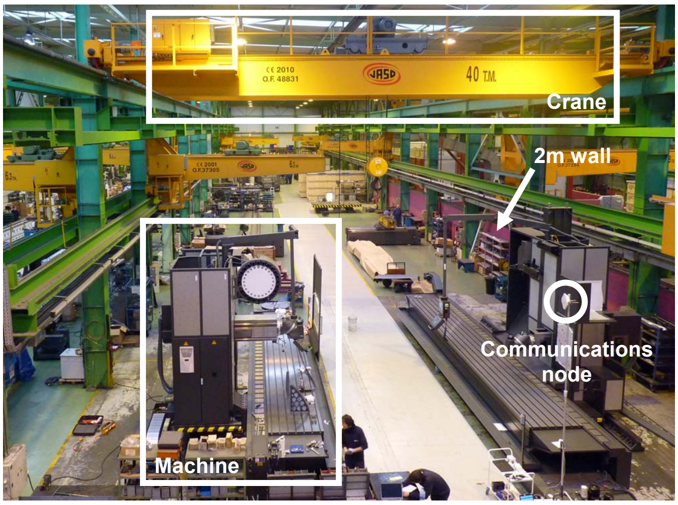

Figure 2. View of one of the corridors at GORATU's factory.

III. Wireless Connectivity for Mobile Sensing

A series of measurements of the wireless connectivity that a mobile sensor node could experience as a worker (or industrial vehicle) walks around a factory has been conducted. In the experiments, the receiver node was located at position *A* in Figure 3, 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. During the experiments, 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 configured to periodically transmit a data packet every T=200ms with a payload of 50bytes excluding headers, emulating the data transmissions of a body sensor device. Figure 3 shows the path followed by the transmitter node, starting in point *A* (near the receiver node), then moving from point *B* to point *G* in alphabetical order.

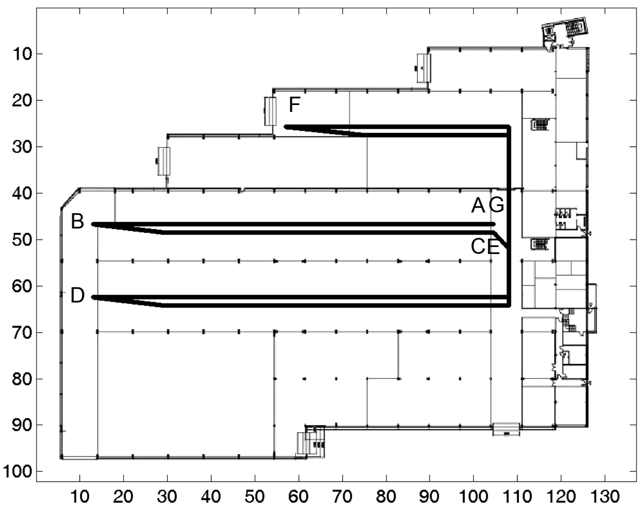

Figure 3. Movement of the transmitter node across GORATU's factory.

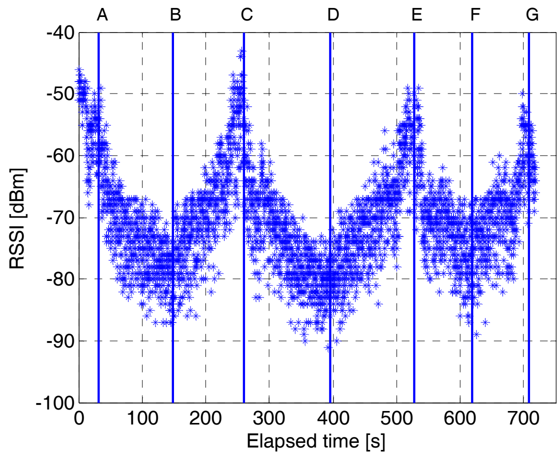

Figure 4. RSSI of the received packets as the mobile transmitter node moves across GORATU's factory. Pt=3dBm, h_T=1.2m, h_R=5m, T=200ms, *payload*=50Bytes.

Figure 4 shows the RSSI of all the received packets as a function of the elapsed time for one of the conducted experiments. To associate the measured values to the locations identified in Figure 3, these locations have been marked on top of Figure 4 (*A*, *B*, *C*, etc.). Along its path, the mobile node experiences different propagation conditions, ranging from LOS (Line of Sight) at short distances (points *A*, *C*, *E* and *G*) LOS with reduced obstructions (point *B*), and partial NLOS (Non Line of Sight) due to cranes, pillars, and machinery (points *D*, and *F*). The varying propagation conditions experienced in the different areas of the factory strongly influence the propagation loss and the resulting signal variability as shown in Figure 4. The signal loss and variability also impacts the measured mobile connectivity as reported in Figure 5. Figure 5 plots the Packet Error Rate (PER) measured in the last T_P=5s at the mobiles nodes, and the accumulated PER experienced along the path. The accumulated PER was below 1% during all the experiment. The instantaneous PER increased to levels close to 8%, but only at sporadic points. A higher value of T_P would provide higher PER resolution, but the use of a lower T_P reduces the time/area over which the instantaneous PER is computed, and therefore better reflects the potentially different PER levels at the different areas of the factory. The obtained results demonstrate that good connectivity levels can be guaranteed for mobile sensing nodes in the considered operating conditions. Such levels could be further improved, for example with a finer optimization of the position of the receiver node, the use of RF power amplifiers, or the establishment of a mesh network with multiple nodes that can forward messages through multi-hop communications.

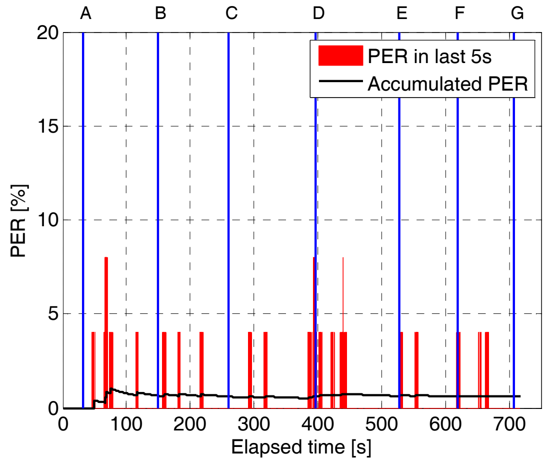

Figure 5. Packet Error Rate experienced as the mobile transmitter node moves across GORATU's factory. Pt=3dBm, h_T=1.2m, h_R=5m, T=200ms, *payload*=50Bytes

IV. COLLISION AVOIDANCE USE CASE

The industrial partners of the FASyS consortium have identified 54 use cases or applications that represent typical problems and dangerous situations currently experienced in factories, and that could be addressed with FASyS technological solutions. The use cases identified include, among others, intelligent alarm activation, differential diagnosis, primary intervention protocols, and ergonomic monitoring. Some of the identified use cases and applications can strongly benefit from the use of FASyS's heterogeneous wireless platform. One of these use cases is aimed at preventing collisions between workers and fork-lift trucks, or between any types of vehicle within a factory. To this aim, FASyS is investigating the possibility to equip workers and vehicles with wireless devices (in this case, WSN motes) so that they can establish a communications link, and exchange information about their position and speed. With this information, they could be able to detect in advance, and avoid, potential dangerous situations. Although the final implementation of this use case would require solving additional technical problems that are currently being investigated in FASyS, such as the design of an HMI (Human Machine Interface) and the availability of precise indoor positioning solutions, the first step would be to analyse whether robust and reliable wireless communication links can be established between any two nodes with a risk of collision, even under challenging propagation conditions. To this aim, experiments emulating the use case have also been conducted at GORATU. In the conducted experiments, two mobile nodes emulate an intersection collision at the location illustrated in

Figure 6. 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. One of the nodes (at an antenna height of h_w=1.2m) emulates the movement of the worker, while the second node (at an antenna height of h_f=1.8m) emulates the movement of a fork-lift truck travelling at a higher speed.

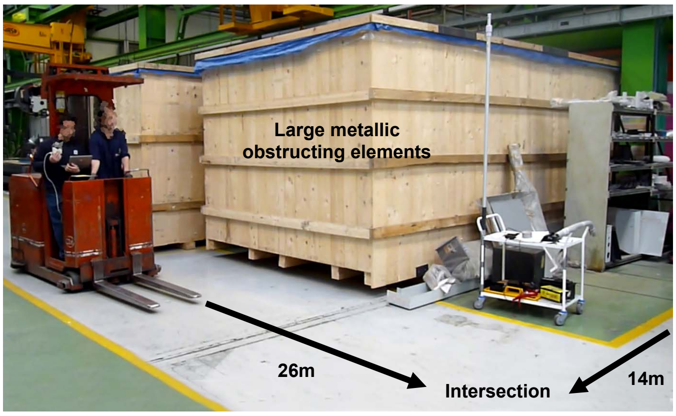

Figure 6. Image of GORATU's factory with the trajectories of the two nodes emulating the collision avoidance use case.

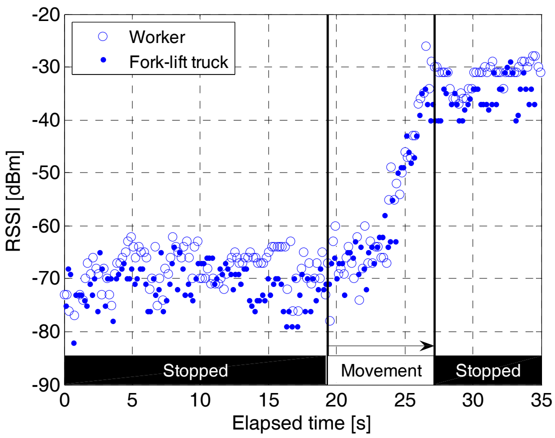

Figure 7. RSSI of the received packets for the collision avoidance use case. Pt=3dBm, h_w=1.2m, h_f=1.8m, T=200ms, *payload*=50Bytes.

The experiment was conducted 9 times to improve the statistical validation of the results, with the nodes periodically transmitting a data packet every T=200ms with a payload of 50Bytes excluding headers and a 3dBm transmission power. Figure 7 plots the RSSI for all the received packets at both the mobile worker and the fork-lift truck. The vertical lines represent the time instants at which the nodes start and stop moving. As it can be observed, the similar RSSI values obtained at the two nodes demonstrates the symmetry of the link. The figure also shows that relatively stable RSSI values are obtained when the two nodes are stopped. However, an increase of around 40dB is produced during the movement phase until the nodes reach the collision point. Such increase is due to a reduced distance between the nodes as they progress towards the collision area, and a smaller influence of the obstructing elements. Despite the bad visibility and propagation conditions between the two nodes during the experiments, all transmitted packets were correctly received by the other node. As a result, it was possible to establish a reliable wireless connection between the two nodes with sufficient time for the driver/worker to react and avoid the collision. These results demonstrate that the use of wireless communications can represent a very attractive solution to establish reliable links among mobile nodes, and avoid potential collisions in industrial environments.

V. CONCLUSIONS

The development of the Factories of the Future (FoF) concept should not only focus on increasing the technological base of manufacturing and the factories' productivity, but also on improving the workers' health and safety. In this context, distributed and mobile sensing technologies could offer interesting solutions to sense in real-time the working environment and worker's conditions, and detect in advance potentially dangerous situations so that preventing actions can be taken. However, the deployment of low power and cost wireless solutions in industrial environments is challenged by the potentially harsh radio propagation conditions that could degrade their transmission quality. Different studies have analysed and characterized the different propagation effects that can be found in industrial environments, but little work was done to date with regards to the propagation and connectivity conditions of mobile sensing devices. In this context, this paper has presented different experiments conducted at GORATU's manufacturing plant to analyse the viability and quality of IEEE 802.15.4/ZigBee transmissions. The conducted experiments have shown that good connectivity levels can be achieved under the considered operating conditions by mobile sensing applications based on IEEE 802.15.4/ZigBee, and that this technology can be a viable candidate to develop innovative health and safety use cases.

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