An Experimental Evaluation of Redundancy in Industrial Wireless Communications

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Abstract—**Industrial wireless communications will be an important technology enabler for the Industry 4.0 paradigm. However, the pervasive introduction of wireless communications in factories requires improving their reliability and capacity to support low latency communications. An approach to do so is through the introduction of redundancy. Several studies have analytically and through simulations demonstrated the benefits of exploiting redundancy in industrial wireless communications. This paper progresses the current state of the art by experimentally analyzing for the first time the benefits that redundancy in industrial wireless communications can provide to support mobile industrial applications. The analysis has been conducted in a collaborative robotics experimental facility under the framework of the H2020 AUTOWARE project.**

Keywords— Industry 4.0, redundancy, industrial wireless networks, prototype, experimental, reliability, latency, mobile.

I. INTRODUCTION

Industry 4.0 (or Factory of the Future, FoF) targets the digital transformation of the manufacturing industry for the implementation of more advanced, adaptive and zero-defect production systems [1]. The development of the Industry 4.0 vision requires connected and networked factories that facilitate the reliable, fast and deterministic transmission and management of data. This requires resilient communication networks capable to efficiently operate at different time scales under harsh industrial environments. Industrial networks have traditionally relied on wired (fieldbus or Ethernet-based) communications. However, wireless communications can provide connectivity to mobile objects (e.g. robots, machinery or workers) and facilitate the flexibility and reconfigurability of factories [2]. The capacity of wireless networks to provide pervasive connectivity is hence fundamental to the development of the Industry 4.0 vision. However, industrial wireless networks must be designed so that they can cope with the high variability and impairments of the radio channel that can be further exacerbated in the harsh industrial environments.

Diversity can improve the reliability of wireless communications. For example, devices might exploit multiple wireless interfaces to transmit using different frequency bands or wireless technologies. A dynamic selection and configuration of the most adequate interface will ensure an efficient use of the communication channel. However, it requires the capacity to detect changes in the communication conditions, and to react to such changes. Detecting the communication conditions and reacting upon them might not be immediate [3], which might affect the capacity to guarantee the deterministic latency requirements that generally characterize industrial applications [4]. An alternative is the use of redundant wireless communications. The Parallel Redundancy Protocol (PRP) –specified in IEC 62439-3 for real-time Ethernet (RTE) technology– proposes to transmit two copies of the same frame through two different networks/paths. By doing so, the PRP protocol reduces the transmission latency and the likelihood that a packet is not delivered to the destination [5]. This is confirmed by [5] that analyzes by means of simulations the performance of PRP over WiFi. Most of the studies that analyze the reliability and latency performance of industrial redundant wireless communications are analytical or simulation-based, with the exception of [6]. However, to the authors' knowledge, no study has previously analyzed experimentally the capacity of redundant wireless communications to support mobile industrial applications. This paper progresses the current state of the art by studying such capacity through the implementation and testing of an industrial redundant wireless communications prototype for mobile industrial applications. This prototype (see Fig. 1) has been developed within the H2020 AUTOWARE (Wireless Autonomous, Reliable and Resilient Production Operation Architecture for Cognitive Manufacturing) project [7]. The prototype wirelessly connects a dual-arm robot and a mobile robotic platform that supplies components to the dual-arm robot. Both robots must be able to continuously communicate. The experiments reported in this paper show that the implemented redundant wireless communication solution guarantees such continuous communication while reducing the end-to-end communication latency.
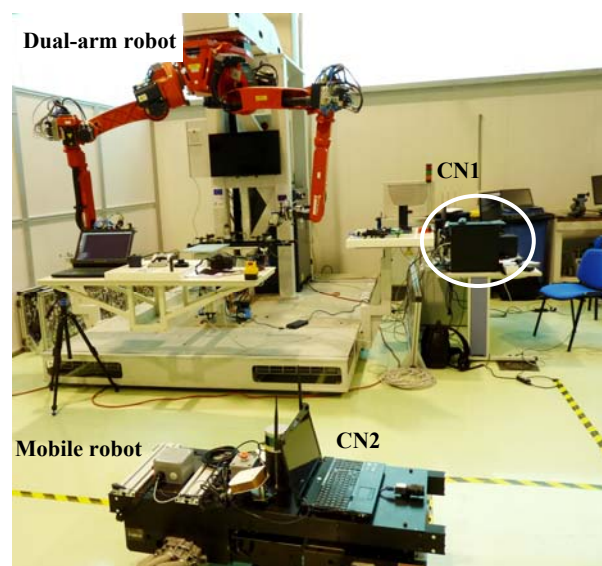

Fig. 1. Collaborative robotics experimental facility.

II. COLLABORATIVE ROBOTICS EXPERIMENTAL FACILITY

The industrial wireless communication prototype has been integrated into the IK4-TEKNIKER experimental facility for collaborative robotics. This facility (see Fig. 1) is a standalone workcell deployed in an industrial shopfloor. It

includes a dual-arm robot, a mobile robot, a tool changer, interaction devices, and multiple sensors for safety and interaction. The mobile robot is expected to supply components to the dual-arm robot. The dual-arm robot requests a component to the mobile robot and indicates where this component is located. The mobile robot calculates its own trajectory, and autonomously moves within the industrial shopfloor to collect the requested component and bring it to the dual-arm robot. The dual-arm robot continuously asks the mobile robot for its position to make sure it heads towards the correct location of the component. If it doesn't, the dual-arm robot will correct the trajectory of the mobile robot using the wireless connection between both robots. The complete process stops if communications fail, and hence the importance of integrating a resilient industrial wireless communication network.

III. REDUNDANT WIRELESS COMMUNICATIONS

Fig. 2 depicts the prototype designed to ensure wireless resilient communications between the dual-arm robot and the mobile robot. The prototype establishes two redundant and independent wireless links between both robots, and data packets are duplicated and sent over both wireless links. The current implementation of the prototype uses IEEE 802.11 or WiFi for the wireless links[1]. The dual-arm robot integrates a communications node (CN1) connected to the controller of the robot (wired connection), and to two WiFi Access Points (APs) identified as AP1 and AP2 in Fig. 2. The mobile robot also integrates a communications node (CN2) that is directly connected to a server that is part of the mobile robot. The communications node in the mobile robot (CN2) incorporates two wireless interfaces to communicate simultaneously with the two APs. The communications nodes integrated within the collaborative robotics experimental facility (CN1 and CN2) can be also identified in Fig. 1.
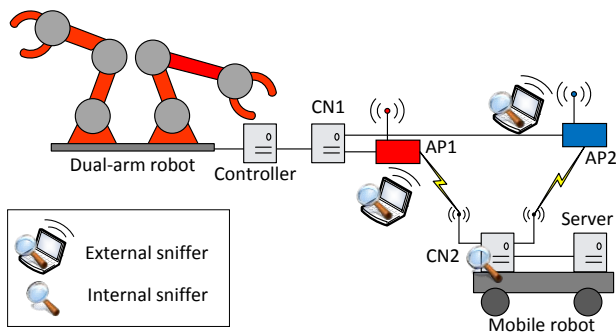

Fig. 2. Implemented prototype.

A TCP client-server application has been implemented within the dual-arm robot and the mobile robot so that both robots can exchange data packets using TCP sockets. To this aim, the dual-arm robot controller establishes first a TCP socket with CN1. Then, CN1 establishes two TCP sockets with CN2. One socket is established through AP1, and the other one through AP2. Finally, CN2 establishes a TCP socket with the TCP server at the mobile robot. The communications nodes manage and process the exchanged data packets at the application layer. CN1 adds a header to the data packets that includes a unique sequence number.

CN1 duplicates each packet and forwards the two copies to CN2; each copy is forwarded using one of the two APs. When CN2 receives the first copy of a data packet, it forwards it to the server at the mobile robot. If CN2 receives later the second copy (identified with the added sequence number), it discards it. A similar process is followed for the data packets transmitted from the mobile robot to the dual-arm robot; the wireless links between both robots are bidirectional.

CN1 and CN2 have been implemented in laptops operating under Linux (using the Ubuntu distribution). CN1 is equipped with three Ethernet interfaces that are used to connect to the dual-arm robot and the two APs. CN2 has a built-in wireless interface, and it has been equipped with an additional external Wireless ExpressCard interface. The built-in wireless interface is used to communicate with AP2, and the external one to communicate with AP1. CN2 integrates an internal packet sniffer application developed by the authors to monitor the transmitted and received 802.11 packets and hence be able to analyze the wireless performance. The sniffer uses the open source <libpcap.h> library to extract information from the header of the 802.11 packets (including the radiotap header). This information includes for example frequency channel, packet size, headers' size, type of packet, RSSI (Received Signal Strength Indicator) and timestamp among others. Sniffers are also utilized to capture the 802.11 packets transmitted and received by the APs and monitor their wireless performance. In this case, the sniffer applications are executed on additional PCs placed next to the APs since their operating system is not open (external sniffer in Fig. 2).

IV. EXPERIMENTAL TRIALS

A. Scenario

Field trials have been conducted at the facilities of IK4-Tekniker. Fig. 3 shows a simplified plan view of the industrial shopfloor where the trials were conducted. The area spans the complete shopfloor that is made up of two open and large rooms. Both rooms have high volume machinery tools such as forming press, robots, wind turbines, and refrigerated cold chambers. Workers freely move around the two rooms, and forklifts are sporadically used to lift and move materials.

Two APs (model TP-Link TL-WA901ND) were deployed to provide wireless coverage in the two rooms (AP1 and AP2 in Fig. 3). The APs were installed at 1-meter height to reproduce harsh propagation conditions with elements (e.g. machinery, robots, workers, forklift) blocking their wireless signals. The APs transmitted using IEEE 802.11g and operated in the non-overlapping channels 1 (AP2) and 11 (AP1) at 2.4 GHz. Each AP then creates a different (and private) wireless network. These two networks coexisted with the permanent 2.4GHz wireless network available at the IK4-TEKNIKER premises.

The dual-arm robot is located in one of the two rooms. The mobile robot must go to the other room to collect the components required by the dual-arm robot. The path of the mobile robot is represented in Fig. 3. At the beginning of a trial, the dual-arm robot requests the mobile robot to collect a component located at mark 6 in the floor map (Fig. 3). The mobile robot is initially located close to the dual-arm robot and the AP1. Upon receiving the request, the mobile robot

moves following the path depicted in Fig. 3. There is approximately 23m between marks 1 and 4. The AP2 is located at the entrance of the second room where the component is located. Upon entering this room, the mobile robot must move 25m before reaching mark 6. It then turns around and comes back to position 1 close to the dual-arm robot. The trial finishes when the mobile robot reaches its initial location. During the trials, the dual-arm robot periodically requests the mobile robot to send its location (one request every 10ms). Upon receiving a request, the mobile robot sends its location. The size of the request and reply data packets is 40 and 29 bytes, respectively. At the beginning of each trial, the NTP (Network Time Protocol) is used at CN1 (dual-arm robot) and CN2 (mobile robot) to synchronize their clocks.
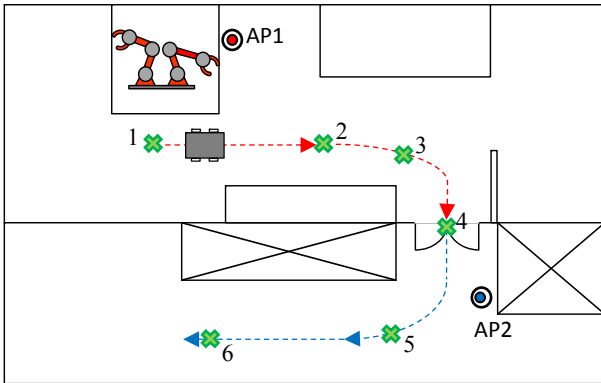

Fig. 3. Simplified floor plan of the industrial shopfloor.

B. Performance results

Several trials have been conducted with different wireless configurations. Fig. 4 shows an example that compares the performance obtained when the mobile robot connects to a single AP and when it uses the proposed redundant wireless solution. All the plots are depicted as a function of the time required by the mobile robot to go from mark 1 to mark 6 in Fig. 3 and to come back to its initial location at mark 1. Fig. 4 represents the wireless performance at the mobile robot although the wireless links between both robots are bidirectional. Fig. 4.a represents the RSSI of the packets received at CN2 (attached to the mobile robot) from AP1 and AP2. Fig. 4.b represents the PER (Packet Error Rate) experienced at CN2 over the wireless links with AP1 and AP2. Fig. 4.c-e depict the transmission latency between CN1 and CN2. The latency is measured as the time elapsed between the time instant CN1 (dual-arm robot) sends a packet and the time instant the packet is received at CN2 (mobile robot). The latency is measured at the application level, and it takes into account possible MAC and TCP retransmissions, and processing times at CN1 and CN2. Fig. 4.c and Fig. 4.d represent the latency experienced in the transmissions from AP1 and AP2 respectively. Fig. 4.e represents the end-to-end latency between CN1 and CN2 when deploying the proposed redundant wireless solution. In this case, packets can be received through the wireless links with AP1 or AP2, and the latency is computed considering the first copy of a packet that is received through either of the two wireless links.
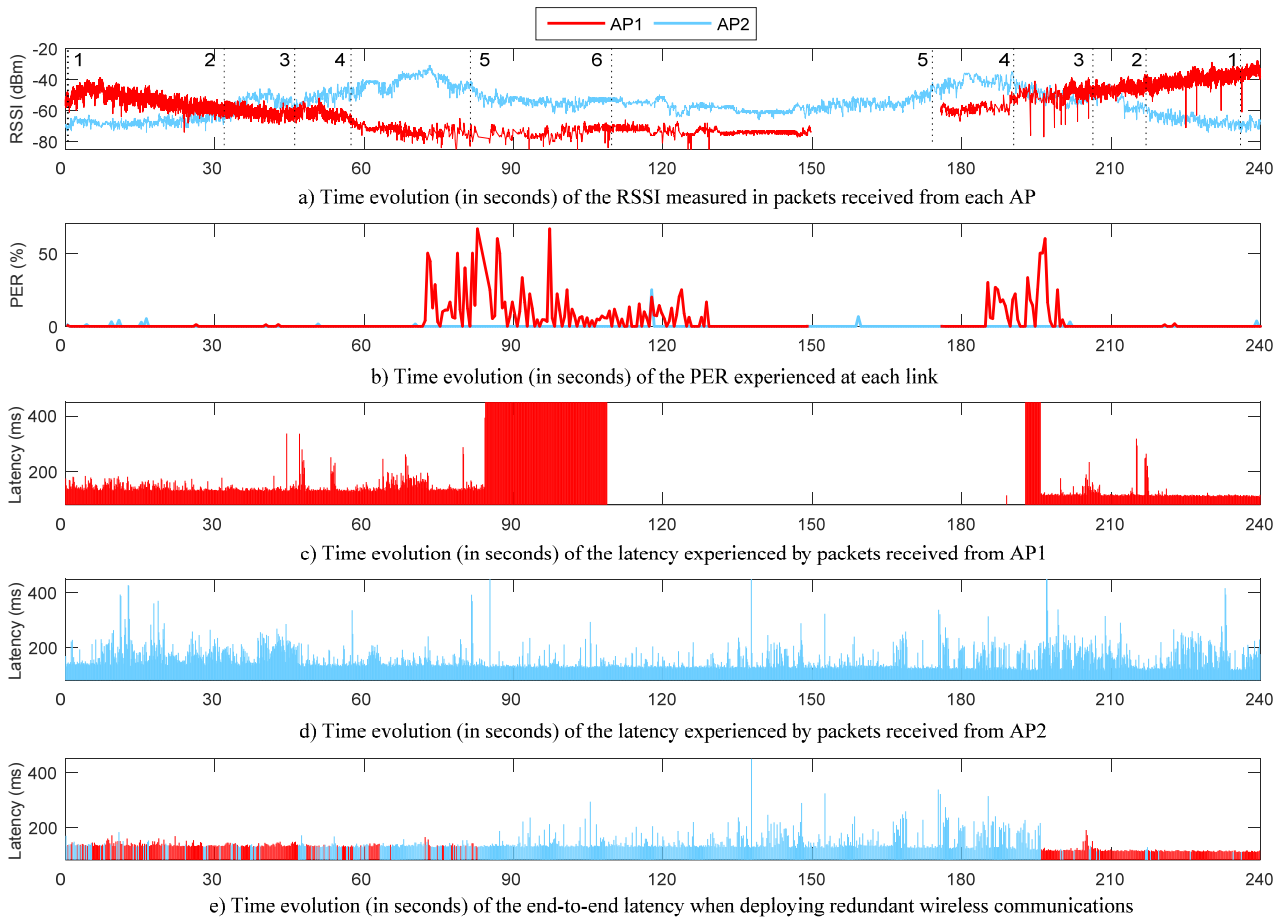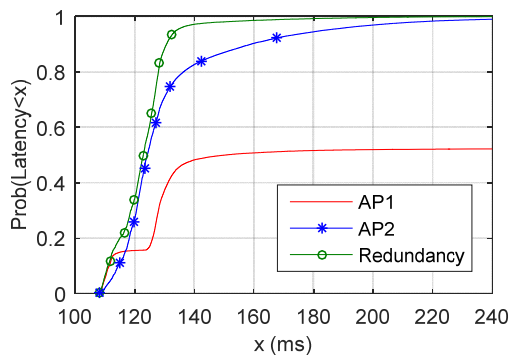

a) Time evolution (in seconds) of the RSSI measured in packets received from each AP

b) Time evolution (in seconds) of the PER experienced at each link

c) Time evolution (in seconds) of the latency experienced by packets received from AP1

d) Time evolution (in seconds) of the latency experienced by packets received from AP2

e) Time evolution (in seconds) of the end-to-end latency when deploying redundant wireless communications

Fig. 4. Experimental wireless performance.

Fig. 5. CDF of the latency.

Fig. 5 that depicts the CDF (Cumulative Distribution Function) of the latency experienced through each wireless link individually (AP1 and AP2), and the CDF of the latency experienced at the mobile robot when implementing redundancy. Redundancy improves the latency and significantly reduces the percentage of packets that experience higher latency values compared to individual wireless links. For example, 46.5% and 20.0% of the packets experienced a delay higher than 136ms when transmitted through AP1 [6] and AP2 respectively. This percentage is reduced to 3.9% with redundancy.

V. CONCLUSIONS

This study has experimentally analyzed for the first time the capacity of redundant wireless communications to support mobile industrial applications. To this aim, a prototype has been implemented within the H2020 AUTOWARE project. The prototype has been designed to support resilient wireless communications between a mobile robot and a fixed dual-arm robot in a collaborative robotics industrial shopfloor. The conducted experiments have shown that redundancy can help overcome some of the limitations traditionally affecting wireless communications in harsh industrial environments (e.g. signal variability or link outages), and improve the reliability and latency of industrial wireless communications. The prototype is currently being extended to integrate multipath TCP and to evaluate its robustness against interference.

Fig. 4 demonstrates the benefits of introducing redundancy in industrial wireless communications. This is clearly observed in Fig. 4.e that shows that redundancy significantly reduces the end-to-end latency compared to the scenarios in which CN2 only receives packets from AP1 (Fig. 4.c) or AP2 (Fig. 4.d). Fig. 4 shows that from t=85s to t=190s the mobile robot loses the connection with AP1 (link outage). This time period corresponds to the time during which the mobile robot is in between marks 4 and 6 (Fig. 3). During this time, the wireless link between AP1 and the mobile robot experiences harsh propagation conditions that significantly reduce the RSSI (Fig. 4.a) and augment the PER (Fig. 4.b) before the connection is dropped[2]. Packets sent through AP1 during this time period experience very high latency levels. For example, 10.4% of the transmitted packets (those transmitted between t=85s and t=110s approximately) experience latency values higher than 105s[3]. In addition, during the link outage, 36% of the packets sent through AP1 do not reach the destination[4]. The introduction of redundancy to improve the resiliency of industrial wireless communications results in that the end-to-end connection is not compromised; during the link outage with AP1 the dual-arm and mobile robots can still communicate through AP2[5].

Redundancy also helps combat the variability of radio propagation in harsh industrial environments. This can be observed in Fig. 4.e when the mobile robot is moving between marks 1-3 (from t=0s to t=45s and from t=200s to t=240s) and experiences NLOS (Non-Line-of-Sight) conditions with AP2. These conditions reduce the RSSI (Fig. 4.a) and increase the variability of the latency experienced by the packets sent through AP2 (Fig. 4.d). On the other hand, during this period the mobile robot is under LOS conditions with AP1, and packets transmitted through AP1 experience significantly lower latency levels (Fig. 4.c). Redundancy can hence combat the inherent variability present in radio communications by providing the receiver the possibility to select on a per-packet basis the wireless link that experiences the best communication conditions (Fig. 4.e). This increases the reliability of the end-to-end links and as a result reduces the end-to-end latency levels. This can be also observed in

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[2] The connection with AP1 is re-established again at t=190s.
[3] The transmission of packets is based on TCP. Packets are stored in the transmitter's buffer until they are correctly received at the destination. If a wireless link is in outage, packets generated during the outage period are stored in the buffer and are transmitted when the link is re-established.
[4] Packets are lost due to the overflow of the transmitter's buffer.
[5] One of the trials conducted at the Tekniker facilities can be watched at https://goo.gl/1fyrp5.

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[6] 36% of the packets are actually lost through AP1.