AUTOWARE

Wireless Autonomous, Reliable and Resilient Production Operation Architecture for Cognitive Manufacturing

D2.3 AUTOWARE Wireless Industrial Communications and Networking

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Executive Summary

This public deliverable (D2.3) describe AUTOWARE's contributions towards the design of low latency and high reliability deterministic industrial wireless networks capable to support more flexible and reconfigurable CPPS. These research activities are carried out as part of the AUTOWARE task T2.3 "Wireless industrial communications and networking for flexible automation". Industrial wireless communications will be an important technology enabler for the Industry 4.0 paradigm. Industry 4.0 (or Factories of the Future, FoF) targets the digital transformation of the manufacturing industry for the implementation of more advanced, adaptive and zero-defect production systems. The development of the Industry 4.0 vision requires connected and networked factories that facilitate 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. The use of wireless communications within factories will facilitate the flexibility and reconfiguration capability sought under the Industry 4.0 framework. In this context, task T2.3 aims to design industrial wireless communications networks able to comply with the stringent and varying communication requirements of industrial applications and services in terms of reliability, latency/determinism and bandwidth, and able to meet the flexibility and reconfiguration capabilities required by the Factories of the Future.

Keywords

Industrial Wireless Communications, Deterministic, Low-Latency, High-Reliability, Self-organizing, Flexible, Reconfigurable, Hierarchical, Heterogeneous, Industry 4.0, Mobile Industrial Applications, CPPS

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Acronyms

A/D	Analog to Digital
ACK	Acknowledge
AN	Announcement
AP	Access Point
AR	Augmented Reality
CDF	Cumulative Distribution Function
CF	Collision Free
CN	Communication Node
CPPS	Cyber-Physical Production Systems
D/A	Digital to Analog
eMBB	Enhanced Mobile Broadband
eNB	enhanced Node B
FCS	Frame Check Sequence
FoF	Factory of the Future
HD	High Definition
IN	Interference Node
ITU	International Telecommunication Union
IWM	Industrial Wireless Network
LM	Local Managers
LOS	Line Of Sight
LUT	Look Up Table
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine Type Communications
MPTCP	MultiPath TCP
NFV	Network Function Virtualization
NLOS	Non Line of Sight
NR	New radio
OFDM	Orthogonal Frequency-Division Multiplexing
PCF	Point Coordination Function
PER	Packet Error Rate
PLCP	Physical Layer Convergence Procedure
PRP	Parallel Redundancy Protocol
RAN	Radio Access Network
RSSI	Received Signal Strength Indicator
RTE	Real-Time Ethernet
RTT	Round-Trip delay Time
SDN	Software Defined Networking

SDR	Software Defined Radio
SNR	Signal to Noise Ratio
SPS	Semi-Persistent Scheduling
SR	Scheduling Request
TCP	Transport Control Protocol
TTI	Transmission Time Intervals
UE	User Equipment
UL	Uplink
URLLC	Ultra-reliable and Low-latency Communications
USRP	Universal Software Radio Peripheral
VR	Virtual Reality

1 Introduction

The digitalization of industry will result in a wide range of changes to manufacturing processes, operation and systems. All these transformations are defined under the concept of Industry 4.0 [1]. Industry 4.0 is based on the interconnection and computerization of traditional industries (such as manufacturing) to enable smart and adaptable factories that efficiently utilize resources and integrate components and systems [2]. A key Industry 4.0 technological enabler is the communication infrastructure that will support the ubiquitous connectivity of Cyber-Physical Production Systems (CPPS) [3,4]. Industrial networks have traditionally relied on wired (fieldbus or Ethernet-based) communications. However, wireless communication can provide connectivity to mobile objects (e.g. robots, machinery or workers) and facilitate the flexibility and reconfigurability of factories [5]. The capacity of wireless networks to provide pervasive connectivity is hence fundamental to the development of the Industry 4.0 vision.

Industry 4.0 is one of the most demanding verticals considering the high variability and stringent communications requirements of different applications and services that will coexist with respect to the number of connected nodes, ultra-low latencies, ultra-high reliability, energy-efficient and ultra-low communication costs [6]. The varying and stringent communication requirements of the industrial applications, together to the harsh propagation conditions and the highly dynamic nature of the industrial environment, pose an important challenge for the design of the communication network. The communication network must be flexible and capable of meeting the communication requirements of the industrial applications, with particular attention on time-critical automation.

The objective of the AUTOWARE project is to design an open CPPS (Cyber Physical Production Systems) ecosystem that provides digital automation cognitive solutions for the manufacturing processes in the factories of the future. Within AUTOWARE, we consider the new concept of multi-layer and decentralized factory IT systems, where intelligence is spread among the manufacturing system, machinary, controllers, and centralized cloud/fog platforms. As previously mentioned, a key technological enabler to achieve this concept is the communication network that will support the ubiquitous connectivity of CPPS. Figure 1 depicts the AUTOWARE general reference architecture defined in deliverable D1.3a [7] that establishes four functional layers -Enterprise, Factory, Workcell/Production Line, and Field Devices- and two additional transversal layers -the

Fog/Cloud and the Modelling layers-. As shown in this figure, the communications network (considering wired and wireless technologies, studied in T2.2 and T2.3 respectively), together with the data management strategies (studied in T2.4), enables the data exchange between the different AUTOWARE components. It provides communication links between devices, entities and applications implemented in different layers, and also within the same layer. The communication network can be represented as a transversal layer that interconnects all the functional layers of the AUTOWARE reference architecture (see Figure 1). The communication network then supports the data management schemes that will enable efficient data distribution within the Factories of the Future.

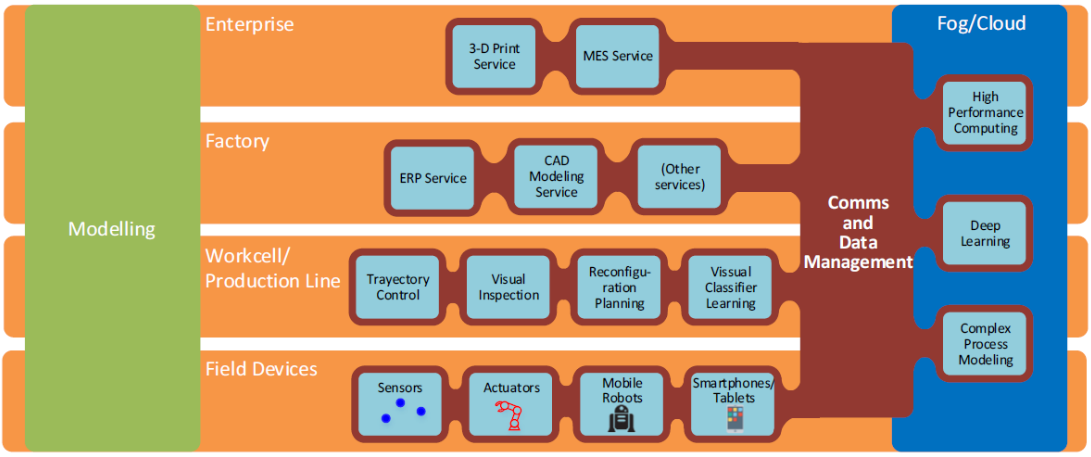


Figure 1. Communication network and data management system into the AUTOWARE reference architecture (user plane) [8].

1.1 Objective

Task 2.3 focuses on the study of innovative solutions for low latency and high reliable deterministic industrial wireless communications. The different studies that are being carried out within T2.3 take as a reference the communications and networking architecture defined in T2.1. In line with the defined architecture, the different proposals are based on a hybrid and hierarchical management that considers decentralized and distributed management decisions; these introduce partial flexibility in the management of wireless connections, while maintaining a close coordination with a central network manager referred to as Orchestrator, as shown in Figure 2. Figure 2 shows the reference communications and networking architecture defined in T2.1. As presented in Figure 2, various Local Managers (LMs) are distributed within the plant located at different workcells or production lines. A central Orchestrator is in charge of the coordination and the global management of the communication resources used by the different sub-networks. Figure 3 shows some of the communications management functions in charge of the different management entities. This figure also shows the integration of communications management with the data management functions that are being developed within T2.4.

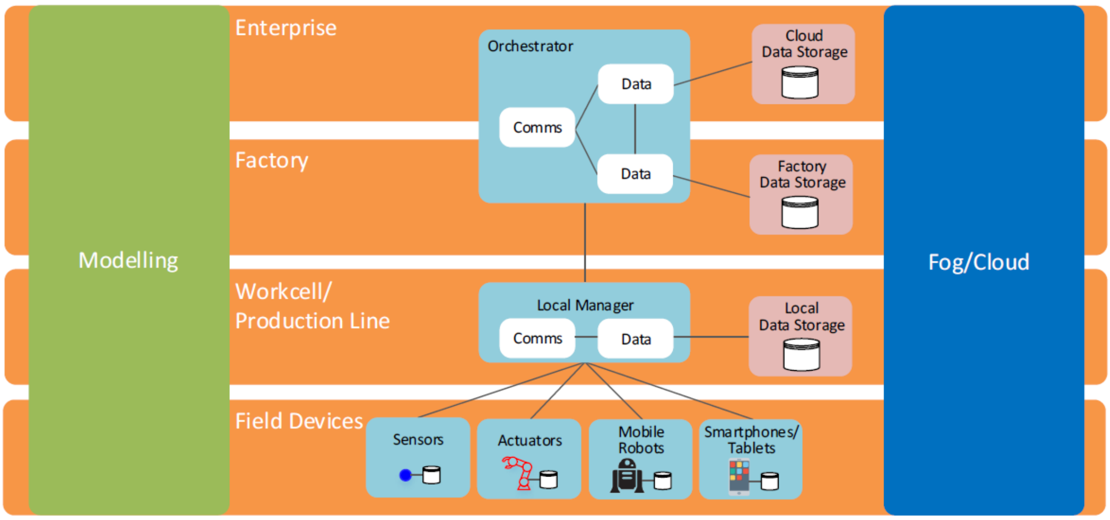


Figure 2. The hierarchical and heterogeneous reference communications and networking architecture (control plane) [8].

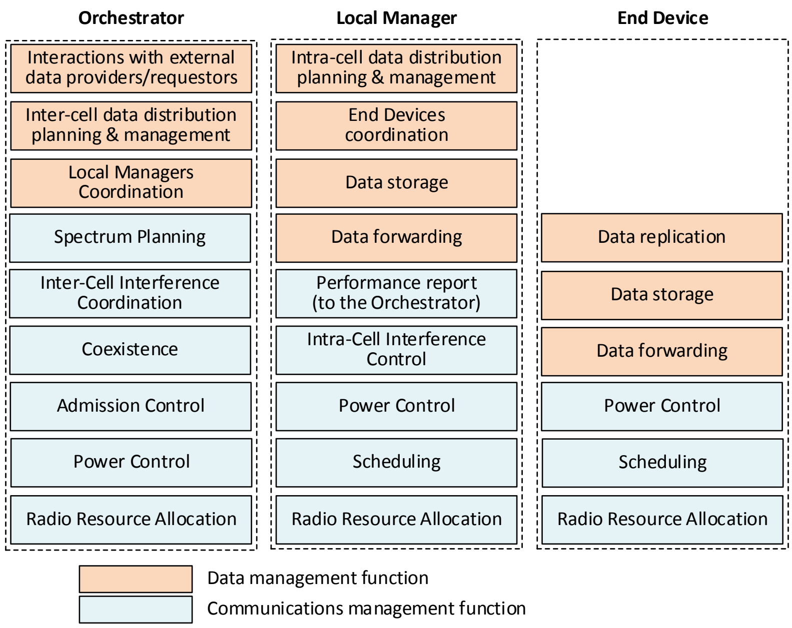


Figure 3. Different communication and data management functions [8].

The hierarchical management scheme proposed within the AUTOWARE reference communications and networking architecture also leverages the deployment of flexible and reconfigurable communications networks. This is the second general objective of T2.3. T2.3 aims at designing flexible and self-organizing industrial wireless networks where the time needed to reconfigure and reprogram industrial wireless connections was minimized, and the need of human intervention in the reorganization and reconfiguration of industrial wireless networks was considerable reduced or even eliminated. In this context, this task also studies and designs management schemes that continuously monitor the communications performance, detect unexpected impairments, and rapidly adapt their configuration.

To achieve these general objectives, this task started with the study and analysis of the existing wireless communication technologies (wireless sensors, wireless local and cellular networks), and its suitability and potential to satisfy the stringent requirements in terms of communications of industrial automation applications. This study resulted in the identification of two main research lines:

1) In the first one, we study solutions to provide reliable communication in industrial wireless networks based on wireless technologies developed and widely used for industrial communication, such as WiFi, WirelessHART, ISA100.11a, or IEEE 802.15.4e. The load-balancing scheme for scalable & self-organizing industrial wireless networks presented in Chapter 2, and the prototype for reliable industrial wireless communication presented in Chapter 3 are related to this first research line.
2) In the second research line, we study novel solutions for low-latency/deterministic industrial communication. This study focusses on 4G+ and future 5G networks considering the high potential that 3GPP standards present to comply with the stringent communication requirements of reliable low-latency/deterministic industrial communication while also increasing the communication bandwidth. The study about deterministic 5G industrial communciation presented in Chapter 4 fits into this second research line.

1.1 Contributions to other WPs and deliverables

The different studies carried out within T2.3 takes as a reference the communications and networking architecture defined in T2.1 and presented in deliverable D2.1 [8]. In line with the defined communication and networking architecture, proposals made within T2.3 consider a hybrid management scheme where distributed decisions are performed while maintaining close coordination by a centralized management entity. T2.3 takes into account the communication requirements of industrial services and applications, and in particular, those of the different AUTOWARE use cases defined in WP1 and presented in deliverable D1.1 [9]. Particularly, one of the studies carried out within T2.3 developes a prototype to comply with the communication requirements of the Tekniker neutral experimentation facility for intelligent automation applications. Studies carried out within T2.3 also take into account the requirements of the data management strategies developed in T2.4, which are built upon the communication network. Finally, we have also contributed to deliverable D7.2 providing information about available wireless communication standards.

1.1 Deliverable organization

This document is organized as follows. Chapters 2, 3, and 4 present the different studies with respect to wireless communication carried out within WP2 in the first half of the project. Chapters 2 presents a load-balancing scheme proposed for self-organizing industrial wireless networks. Chapter 3 presents the prototype developed for providing reliable industrial wireless communication for mobile industrial applications. In this chapter, the results achieved in experimental trials carried out in the Tekniker neutral experimentation facility for intelligent automation applications are presented. Chapter 4 presents the current study that is being carried out within T2.3 about deterministic industrial 5G communication. Chapter 5 summarizes and concludes the document.

2 Scalable & Self-Organizing Industrial Wireless Networks

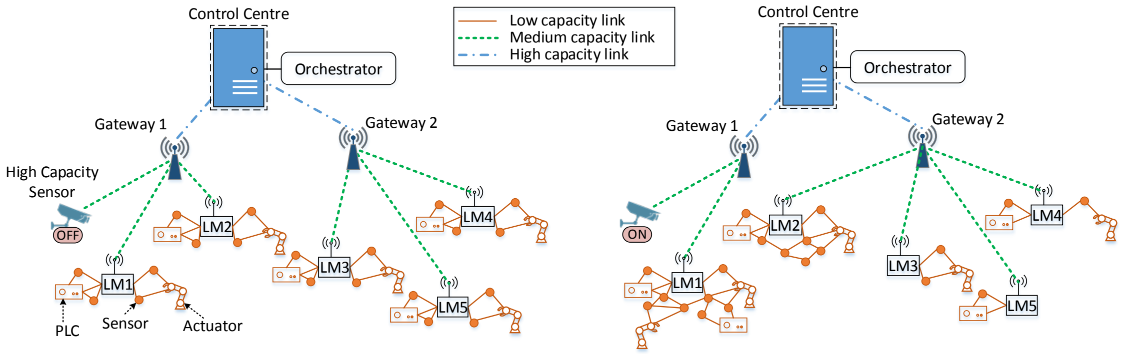
Industrial CPPS systems will be supported by different types of wireless sensors (fixed or mobile; mobile sensors can be associated to workers, mobile machinery or vehicles) that will send data to control centers in charge of controlling and supervising the industrial environment and manufacturing processes. The sensors can be of different nature, and have different communication requirements. For example, temperature sensors will transmit small amounts of data (usually periodically), while IP cameras or 3D scanners sporadically generate large amounts of data that require high bandwidth communication links. Traditional industrial wireless standards such as WirelessHART or ISA100.11a can only support low bandwidth data transmissions. Several studies have then proposed to support future industrial CPPS with hierarchical communication networks ([10,11,12,13]) that integrate and exploit various wireless technologies with different characteristics. In such hierarchical networks, sink nodes are deployed to collect data from different low-bandwidth sensors, and transmit it to gateway nodes using higher bandwidth wireless technologies. The gateway nodes are usually deployed so that they can collect and transmit data from/to various sensors and/or sink nodes. Hierarchical communication systems must be able to support dynamic industrial environments that will result from the coexistence of different type of sensors, varying data demands or generation rates, and the integration of mobile sensors in robots, machinery, vehicles, or even workers. This scenario will generate spatio-temporal variations of the data demand and distribution within factories that require a dynamic management of the hierarchical industrial communication networks. Such dynamic management will be critical to design reliable self-organizing industrial wireless networks. In this context, within T2.3 we have studied a novel load balancing scheme that is capable to dynamically react under changes in data demand and distribution, and avoid the congestion of the wireless communication links and the resulting loss of critical industrial data. In particular, the proposed scheme focuses on balancing the load of links between sink and gateway nodes since they will concentrate mostly on the industrial data traffic. The load balancing decisions are based on the quality of the wireless links and the amount of data that each node must transmit. The conducted evaluation demonstrates that the proposed scheme reduces channel congestion and significantly improves the reliability of industrial wireless networks compared to existing solutions and static wireless deployments. The proposed scheme also reduces the number of reconfigurations of wireless links, and therefore the signaling overhead generated when deploying self-organizing industrial wireless networks.

2.1 Industrial Wireless Networks

WirelessHart, ISA100.11a and IEEE802.15.4e [14,15] are some of the existing standards for industrial wireless communications. These standards are based on the IEEE 802.15.4 physical and MAC (Medium Access Control) layers, and have been designed to support a high number of field devices (sensors or actuators) that require low data rates and energy consumption. These standards centrally manage the network to ensure reliable industrial wireless communication. However, a centralized network management can result in excessive overhead, long reconfiguration times and scalability challenges ([10],[16]). To address these limitations, several studies (e.g. [10]-[13],[17]) have proposed to deploy hierarchical industrial wireless networks capable to integrate multiple sub-networks supported by different wireless technologies and offering different connectivity capabilities. Each sub-network has its own manager and sink nodes. The manager manages the wireless connections of the sub-network, and the sink nodes collect/distribute the data in the sub-network. The manager of a sub-network is referred to in this paper as Local Manager (LM)[1]. LM nodes are connected to Gateway nodes in the plant that aggregate data from different LM nodes, and transmit it to remote or on-site control centers and servers. Figure 4.a represents an example of a hierarchical industrial network following the architecture proposed in T2.1 and presented in D2.1 [8] and [17]; in this particular network implementation, the communication link between LMs and the Control Centre, where the central management entity referred to as Orchestrator is located, is a two-hop link for higher flexibility. Several studies (e.g. [11],[12]) have demonstrated that the reliability, delay and energy consumption of industrial networks can be improved when deploying heterogeneous wireless technologies capable to support different communication requirements (e.g. in terms of bandwidth, reliability or communication range). Such deployment can be envisioned within hierarchical industrial architectures such as the one illustrated in Figure 4.a. For example, WirelessHart, ISA100.11a and IEEE 802.15.4e can be utilized to support and manage sub-networks of sensors and actuators with low data rates. IEEE 802.11 (WiFi) or cellular technologies provide significantly higher bandwidth than industrial wireless standards, and their integration in the hierarchical industrial communication architectures could be key to support the development of the Industry 4.0 paradigm. In fact, several studies have recently demonstrated the potential of IEEE 802.11 (or WiFi) ([18],[19],[20]) and cellular technologies ([21]) to support industrial applications. The bandwidth of WiFi or cellular technologies make them suitable candidates to connect various LM nodes to Gateway nodes, and even to directly connect high capacity sensors (e.g. video cameras) to

[1] A LM is equivalent to a Network Manager in WirelessHART or a System Manager in ISA100.11a.

Gateway nodes as illustrated in Figure 4.a. The Gateway nodes can be connected to remote or on-site control centers or servers using large-capacity (fixed or wireless) backhaul links.



a) Initial configuration. *b) Reconfiguration under changes in the spatial distribution of data.*

Figure 4. Hierarchical communications architecture in industrial wireless networks (D2.1 [8] and [17]).

Several studies have demonstrated the benefits provided by hierarchical industrial networks (e.g. [10]-[13]). These networks can play a significant role in the development of the Industry 4.0 if they are able to support data-intensive applications and the foreseen spatio-temporal variations of data demand and distribution in factories. Such variations can challenge the reliable, timely and efficient transmission of data, and require flexible and agile networks capable to dynamically reconfigure the wireless connections. An example of this challenge is illustrated in Figure 4. The initial configuration of the network in Figure 4.a was capable to adequately collect all data at the LMs and transmit it to the Control Center through the Gateway Nodes. However, in Figure 4.b, a higher number of sensor nodes are connected to LM1 and LM2, and the high-bandwidth camera has been activated. All these changes significantly increase the load at Gateway 1 with the subsequent risk of saturating its channels and lose critical industrial data. To avoid this scenario, it is necessary that the network detects the spatio-temporal variation of the data and reconfigures the network connections to avoid any possible link saturation. This is done in Figure 4.b by balancing the load of the wireless links, and connecting LM2 to Gateway 2. This example illustrates the need for industrial wireless networks to embed load balancing schemes capable to monitor the status of wireless connections, detect possible risks of channel saturation that can result in the loss of critical industrial data, and be able to effectively distribute the data load among the available wireless nodes.

2.2 Related work

Load balancing schemes have been proposed for conventional cellular and wireless networks with the objective to improve the network performance. For example, [22] proposes a scheme that balances the load among access points or base stations in order to avoid saturating backhauls links in a heterogeneous cloud radio access network. The scheme utilizes more efficiently the resources, and hence improves the network performance. In [23], the authors propose a user association scheme for a network with several small cells and an overlapping macro cell. The proposed scheme decides which cell should serve each user by solving an optimization problem designed to maximize the throughput experienced by all users. The study shows that the maximum throughput is achieved when the scheme is capable to distribute the load among the different cells.

To the authors' knowledge, the only study that analyzes the application of load balancing in industrial wireless networks was presented in [24]. In [24], devices wirelessly communicate with Access Points (APs) that are connected to a global controller through a wired backbone. The scheme presented in [24] distributes devices between APs in order to maintain the load at each AP equal to the average network load (a maximum deviation per AP is allowed). The load of an AP is estimated in [24] as the total bandwidth required by all devices connected to the AP with respect to the total bandwidth available at the AP. This metric does not take into account the link quality of the wireless connection between the device and the AP. This can be highly relevant since a device with poor link quality will require much more bandwidth to transmit a given amount of data than another one with much better link quality. An alternative metric for load balancing is the length of the data queue of a node ([25,26,27]). In [25], the authors propose a load balancing algorithm that distributes the load between nodes of a wireless mesh network based on their level of congestion. The level of congestion is estimated as the average length of the data queue at a node. The study found that load balancing schemes that take into account the nodes' level of congestion significantly improve the throughput and reduce the delay.

In this context, this study proposes a novel load balancing scheme and metric for industrial wireless networks. The scheme is designed with the objective to support the spatio-temporal variations of data demand and distribution in factories of the future. The proposed scheme bases its load balancing decisions on a metric that estimates the time the channel is utilized, and that can be easily estimated by the nodes. This study demonstrates the proposed metric and scheme significantly improve the reliability of industrial wireless networks compared to static network deployments and alternative schemes.

2.3 Load Balancing Proposal

2.3.1 Framework

We adopt the Industrial Wireless Network (IWN) proposed in [13] and illustrated in Figure 4. In addition, we consider that the management of this IWN is based on a hierarchical management architecture as proposed in T2.1 (D2.1 [8] and [17]). In this context, the Control Centre includes an Orchestrator that manages the complete IWN. The LM and Gateway nodes continuously monitor the link level performance (in particular, the Signal to Noise Ratio, SNR) of all their links, and periodically report it to the Orchestrator. The LM and Gateway nodes also include in the periodic reports information about the amount of data (in bps) received from the lower level to be transmitted to the Control Centre. The Orchestrator uses these reports to manage and reconfigure all the network connections in order to ensure the reliable, timely and efficient collection and distribution of data in the factory. This study focuses on balancing the load between Gateways by dynamically managing the connections between LM nodes and Gateways[2]. The links between LM and Gateway nodes are critical since the LM nodes aggregate and transmit the data collected from various sensors. This study considers the use of IEEE 802.11 (or WiFi) to wirelessly connect LM and Gateway nodes. The Gateway nodes act as Access Points (APs), and utilize IEEE 802.11a with Point Coordination Function (PCF)[3] to manage the access to the channel of the attached LM nodes and prevent packet collisions [18]. As a result, a Gateway's channel can be used to serve several LMs. This study considers that only one channel is used by each Gateway node. In addition, this study also assumes that each LM node is in the communication range of at least two Gateways. This is highly realistic since the reliability levels demanded by industrial applications generally results in the need for redundancy in network deployments.

2.3.2 Load Balancing

The proposed load balancing scheme estimates the load of a Gateway's channel as the ratio of time that the channel is utilized by all the LMs served by the Gateway. The scheme is hence referred to as CUBE (Channel Utilization BalancE scheme). CUBE decides to which Gateway j should each LM i be attached; $i \in [1, L]$, $j \in [1, G]$, L and G are the number

[2] The scheme could also be applied to manage the backhaul connections between the Gateways and the Controller. However, the high bandwidth of these connections significantly reduces the risk of channel saturation.

[3] In PCF, an AP manages the access to the channel by sending polling messages to the attached nodes. Only the node that is addressed in a polling message can transmit at that time.

of LMs and Gateways in the IWN respectively. To this aim, CUBE solves the following objective function (o.f.):

$$\text{o.f:} \quad \min \max_{j} \widehat{CUR}_j \text{, where } \widehat{CUR}_j = \sum_{i=1}^{L} \widehat{CUR}_{ij} \cdot y_{ij} \tag{1}$$

where $\widehat{CUR}_j$ is the estimated load of Gateway j's channel. $\widehat{CUR}_j$ can be expressed as the sum of the estimated load generated by each one of the LMs i served by the Gateway j ($\widehat{CUR}_{ij}$). y_{ij} is a binary variable equal to 1 if LM i communicates with Gateway j and equal to 0 otherwise. Using the objective function in (1), CUBE seeks minimizing the maximum load of the channels of the different Gateways. To this aim, CUBE balances the load of between the channels of the different Gateways. The objective function in (1) can be expressed linearly, and hence the following optimization problem can be defined:

$$o.f: \quad \min K \tag{2}$$

$$\text{subject to:} \quad \sum_{i=1}^{L} \widehat{CUR}_{ij} \cdot y_{ij} \leq K, \quad \forall j \in \{1, \ldots, G\} \tag{2.1}$$

$$\sum_{j=1}^{G} y_{ij} = 1, \quad \forall i \in \{1, \ldots, L\} \tag{2.2}$$

$$K \in \Re, K<1 \tag{2.3}$$

$$y_{ij} \in \{0, 1\} \tag{2.4}$$

The objective function is now defined in (2) and includes the restriction expressed in (2.1). K is defined in (2.3). CUBE guarantees that all LMs are connected to a Gateway following the restriction defined in (2.2). The optimization problem is a mixed integer programming (MIP) problem with binary variables y_{ij} (as established in (2.4)) and a real variable K.

CUBE is executed at the Orchestrator. Each Gateway continously measures the real load experienced in its channel, represented as CUR_j, and sends it to the Orchestrator periodically (every t_{CUBE}). The Orchestrator periodically checks (every t_{CUBE}) for every Gateway j if CUR_j is higher than a predefined threshold CUR_{th}. If it is the case, the Orchestrator executes CUBE to balance the load between the Gateways[4]. The value of CUR_{th} is updated as a function of the optimum value of K, represented by K^*, after the last execution of CUBE. CUR_{th} is updated in order to guarantee a rapid reaction of the CUBE algorithm when the load experienced by the channels of the different Gateways is unbalanced, and finally prevent situations where the robustness and reliability of the

[4] We also evaluated the scenario in which CUBE is executed periodically without observing significant performance benefits. On the other hand, periodically executing CUBE augments by a factor of 4 the number of times LM nodes change their serving Gateway.

network could be compromised. Algorithm I shows how CUR_{th} is updated[5]. This algorithm maintains always a CUR_{th} value slightly higher than K^*: if CUR_{th} is smaller than K^*, CUR_{th} is updated to $K^*+\beta_1$, otherwise CUR_{th} is reduced by a factor of β_2.

ALGORITHM I: CUR_{TH} UPDATE ($\beta_1, \beta_2 \in \mathbb{R}$, $0< \beta_1, \beta_2 <1$

1. **If** $CUR_{th} < K^*$
2. $\quad CUR_{th} = K^*+\beta_1$
3. **Else**
4. $\quad CUR_{th} = CUR_{th} \cdot \beta_2$
5. $\quad$**If** $CUR_{th} < K^*$
6. $\quad\quad CUR_{th} = K^*+\beta_1$
7. $\quad$**End If**
8. **End If**

2.3.3 Load estimation

In order to estimate $\widehat{CUR}_{ij}$, each LM i measures (and periodically reports to the Orchestrator) the value of the SNR with each one of the Gateways under its communication range. The LMs estimate the SNR using the Collision Free (CF)-Poll frames that are periodically transmitted by each Gateway following the IEEE 802.11a standard when configured with PCF. The LM reports to the Orchestrator the SNR values together with the rate at which incoming data enter the queue of the LM ($IRate_i$) to be transmitted to the serving Gateway (see Figure 5). Using this information, the Orchestrator estimates the transmission rate that LM i requires with each Gateway under range in order to transmit the data entering the queue without further augmenting the LM's queue. To avoid augmenting the queue, LM i requires a transmission rate with Gateway j equal or higher than $ORate_{ij}$:

$$ORate_{ij} = \frac{IRate_i}{1\text{-}PER_{ij}} \quad (3)$$

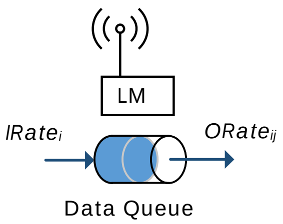
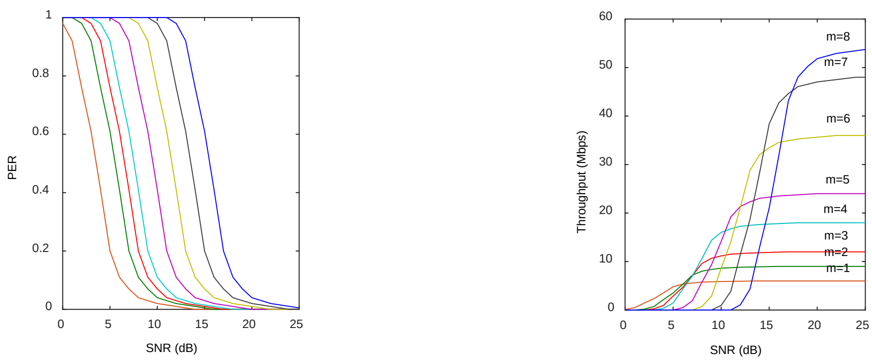


Figure 5. Representation of the data queue of a LM node.

[5] α, β_1 and β_2 are real values. α is set slightly higher than 1, whereas β_1 and β_2 are smaller than 1.

where PER_{ij} is the Packet Error Rate between LM i and Gateway j. The Orchestrator estimates PER_{ij} using the received SNR_{ij} estimates (averaged over t_w) and the LUTs (Look Up Tables) illustrated in Figure 6 (and derived from [28]). These LUTs relate the throughput and PER with the SNR for all possible transmission modes m included in IEEE 802.11a. A transmission mode is a combination of modulation and coding scheme. IEEE 802.11a defines 8 transmission modes, and each transmission mode has a different data rate R. In IEEE 802.11a, the transmitter dynamically selects the transmission mode m that maximizes the throughput for the experienced SNR. Using the average SNR_{ij} estimate and Figure 6.a, the Orchestrator identifies the transmission mode m_{ij} that would maximize the throughput between LM i and Gateway j. Once m_{ij} has been identified, the Orchestrator can estimate PER_{ij} using the average SNR_{ij} and the LUT in Figure 6.b.



a) Throughput as a function of SNR. b) b) PER as a function of SNR

Figure 6. LUTs for IEEE 802.11a.

Considering that L_{max} (in bits) is the maximum packet length in 802.11a, LM i should transmit P_{ij} packets of L_{max} bits and one additional packet of length L bits per second to the Gateway j in order to achieve $ORate_{ij}$, where P_{ij} and L are given by:

$$P_{ij} = \left\lfloor \frac{ORate_{ij}}{L_{max}} \right\rfloor = \left\lfloor \frac{IRate_i/(1\text{-}PER_{ij})}{L_{max}} \right\rfloor \quad (4)$$

$$L = \frac{IRate_i}{(1\text{-}PER_{ij})} - P_{ij} \cdot L_{max} \quad (5)$$

The Orchestrator can then estimate the value of $\widehat{CUR}_{ij}$ that results from the transmission of LM i to the Gateway j using this expression:

$$\widehat{CUR}_{ij} = (P_{ij} - 1) \cdot \hat{T}_{ij}(L_{max}) + \hat{T}_{ij}(L) \quad (6)$$

$\hat{T}_{ij}(L_{max})$ and $\hat{T}_{ij}(L)$ represent the estimation of the time that LM i occupies the channel when it transmits a packet of L_{max} and L data bits respectively to the Gateway j. The PCF mode of IEEE 802.11a requires the transmission of a CF-Poll Frame from the Gateway to the LM before the LM can transmit a data packet to the Gateway. In addition, the LM must wait t_{SIFS} (equal to 16 µs) after the reception of the CF-Poll Frame before it can start transmitting its data packet. The Gateway must also wait t_{SIFS} after it received the last data packet before transmitting another CF-Poll Frame. The time $\hat{T}_{ij}(d)$ that LM *i* occupies the channel when it transmits a packet of *d* data bits to the Gateway *j* is then equal to:

$$\hat{T}_{ij}(d)=t_{Poll}+t_{SIFS}+t_{DATA}(d)+t_{SIFS} \tag{7}$$

where t_{Poll} represents the time necessary to transmit a CF-Poll Frame, and $t_{DATA}(d)$ represents the time necessary to transmit a data packet of *d* bits of data. The time necessary in IEEE 802.11a to transmit a packet of *d* bits of data is equal to:

$$\begin{aligned} t_{DATA}(d) = {} & t_{PLCP-P} + t_{PLCP-H} + t_{MAC-H} \\ & + t(d) + t_{FCS} + t_{tail} + t_{pad}. \end{aligned} \tag{8}$$

where t_{PLCP-P} and t_{PLCP-H} represent the time necessary to transmit the preamble and PLCP (Physical Layer Convergence Procedure) header added in the IEEE 802.11a physical layer. t_{PLCP-P} and t_{PLCP-H} are equal to 16 µs and 4µs respectively. t_{MAC-H} and t_{FCS} represent the time necessary to transmit the 34 bytes added at the MAC layer, and that correspond to the MAC header and the Frame Check Sequence (FCS). $t(d)$ represents the time necessary to transmit *d* data bits. Finally, t_{tail} and t_{pad} represent the time needed to transmit the tailbits and padbits (16 and 6 bits respectively) that IEEE 802.11a adds to each packet prior to its radio transmission. If LM *i* uses a transmission mode m_{ij} (with data rate $R(m_{ij})$) to communicate with Gateway *j*, $t_{DATA}(d)$ is equal to:

$$t_{DATA}(d) = 20\mu s + \frac{34 \cdot 8 + 16 + 6 + d}{R(m_{ij})} \tag{9}$$

On the other hand, the CF-Poll Frame contains a physical layer preamble and PLCP header, a data field of 20 bytes, and tail and pad bits (16 and 6 bits respectively). The CF-Poll Frame packet is transmitted with the more robust transmission mode offering a data rate of 6 Mbps. As a result, t_{Poll} is equal to:

$$\begin{aligned} & t_{Poll} = t_{PLCP-P} + t_{PLCP-H} + t(20 \cdot 8) + t_{tail} + t_{pad} = \\ & 20\mu s + \frac{16 + 6 + 20 \cdot 8}{6 \cdot 10^6}. \end{aligned} \tag{10}$$

Using equations (3)-(10), the Orchestrator can then estimate the value of $\widehat{CUR}_{ij}$ that results from the transmission of LM *i* to the Gateway *j*.

2.4 Reference schemes

The performance obtained with CUBE is compared in this study against that achieved with a static IWN deployment where each LM is permanently connected to the Gateway with which it experiences the higher average SNR. This configuration is the most common in existing deployments, and is referred to in the rest of the paper as fixedGW.

CUBE is also compared to a load balancing scheme that bases its decisions on the length of the data queues at the LMs following the review of the state of the art presented in Section 2.2. In fact, several contributions (e.g. [25]-[27]) utilize this metric for their load balancing proposals. This second reference scheme is referred to in the rest of the paper as QUEUE. For a fair comparison, QUEUE is implemented in this study following a similar approach to that considered for CUBE, but basing all decisions on the queue lengths rather than on the $\widehat{CUR}_{ij}$ metric. In QUEUE, LMs also periodically send to the Orchestrator (every t_q) information about their data queue, in particular, the maximum queue length. QUEUE calculates for each LM i the ratio QR_i between the maximum data queue length $QL_{max,i}$ experienced during the last t_q period and the capacity QC_i of its data queue defined as the maximum amount of data that the data queue can storage:

$$QR_i = \frac{QL_{max,i}}{QC_i} \tag{11}$$

If QR_i is higher than a predefined threshold QR_{th}, QUEUE assigns LM i a different Gateway if the following conditions are met: 1) all the LMs served by the new Gateway must experience a value of QR below QR_{th}, and 2) LM i must have been served by the current Gateway for longer than t_{min}. This last condition is defined to avoid continuous changes of the serving Gateway. In fact, an LM that has recently changed its serving Gateway needs some time to reduce its QR below QR_{th}. If the two conditions are not satisfied for LM i, QUEUE cannot change the serving Gateway for LM i, and will instead try changing the serving Gateway to the LM that experiences the next higher value of QR (even if it is lower than QR_{th}); the change can again only be executed if the two previous conditions are satisfied.

2.5 Evaluation scenario

The schemes are evaluated in a scenario emulating an industrial plant of 300m x 200m with hallways that are 20m wide and that are distributed as illustrated in Figure 7. The scenario includes 3 Gateway and 5 LM nodes. This deployment guarantees wireless coverage in all the plant.

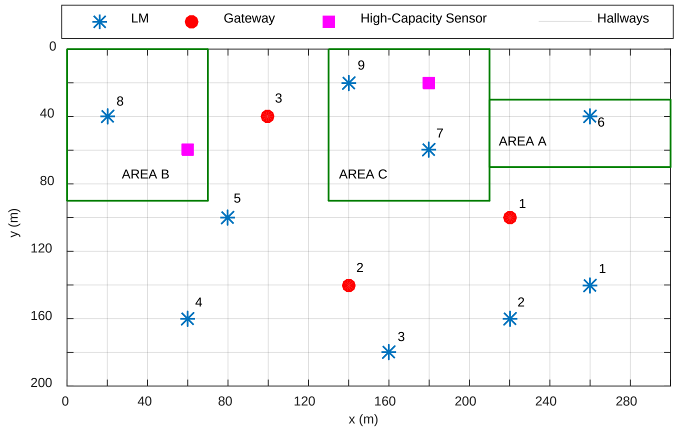


Figure 7. Industrial plant.

400 fixed sensor nodes are homogenously distributed in the plant. The scenario also includes 300 mobile sensor nodes (representing mobile machinery or workers, among others) that move around the plant at constant speed. All (fixed and mobile) sensor nodes transmit 10 packets (of 40 bytes each) per second. Raw sensor data received at the LMs is converted to SensorML format ("Sensor Model Language" international standard) before being forwarded to the Control Centre. This conversion increases the amount of data to be sent by a factor *f* equal to 10 as discussed in [13]. Two different scenarios have been simulated. In both scenarios, mobile sensor nodes can in principle move across the complete plant. However, these nodes tend to concentrate in certain areas of the plant when specific tasks or activities are executed in these areas. When these tasks are completed, mobile sensor nodes can move freely across the plant. The scenarios differ on the duration and location of the tasks, and on the spatial distribution of the sensed data:

- Scenario S1. The tasks are concentrated in the areas A and B (Figure 7). The tasks in A last from $T_{A,s}$ to $T_{A,e}$, and in B from $T_{B,s}$ to $T_{B,e}$. N_A and N_B mobile nodes move to areas A and B respectively during the execution of the tasks (Table 1).

- Scenario S2: The tasks are concentrated in the areas B and C (Figure 7). The tasks in B last from $T_{B,s}$ to $T_{B,e}$,, and in C from $T_{C,s}$ to $T_{C,e}$. N_B and N_C mobile nodes move to areas B and C respectively during the execution of the tasks (Table 1). In S2, IP cameras are switched during the execution of the tasks. The camera produces video at a rate of 10 frames per second (see Table 1). The presence of these cameras significantly increases the data load in the working areas compared to S1. The increase is also more abrupt due to the high bandwidth of the video cameras.

Parameter	Value
L, G (number of LMs and Gateways)	3 ,9
LMs packet size	1500 bytes
LM queue capacity (*QC*)	32 kbytes
Camera frame size	50 kbytes
Camera frames per second	10
Camera queue capacity (QC)	500 kbytes
t_w	1s
t_{CUBE}	0.2s
t_q	2s
SNR_{th}	15 dB
QR_{th}	0.95
t_{min}	5s
Raw data to SensorML format conversion factor, *f*	10
β_1, β_2	0.05, 0.95
S1: $T_{A,s}$, $T_{A,e}$, N_A	110s, 500s,100
S1: $T_{B,s}$, $T_{B,e}$, N_B	100s, 500s, 200
S2: $T_{B,s}$, $T_{B,e}$, N_B	150s, 700s, 100
S2: $T_{C,s}$, $T_{C,e}$, N_C	100s, 500s, 100

Table 1. Simulation parameters.

The industrial scenario is simulated using a C++ simulator developed by the authors. The simulator includes the libraries and functions necessary to interact with the optimization solver IBM ILOG CPLEX [29]. IBM ILOG CPLEX has been used to solve the MIP problems defined by CUBE. The platform simulates the LMs to Gateways connections[6] that implement the load balancing schemes under evaluation. The LMs connect to the Gateway nodes using IEEE 802.11a with its PCF function [30]. The LMs can be simultaneously connected with two Gateways to ensure the reliability of wireless connections. The simulator includes SNR maps (Figure 8) to model radio propagation effects. These SNR maps have been obtained using real measurements (from [20]) in an industrial plant similar to that represented in Figure 7. The SNR map represents the average SNR experienced by a node at distance (*x*, *y*) from an IEEE 802.11a transmitter located at the coordinates (0, 0). The SNR maps were obtained considered the Line Of Sight (LOS) and Non Line Of Sight (NLOS) conditions experienced in an industrial setting such as the one illustrated in Figure 7. The transmitter dynamically selects the IEEE 802.11a transmission mode that maximizes the throughput as a function of the average SNR. Table 1 summarizes the main simulation and scenario parameters.

[6] How data is routed from a sensor node to the LM does not influence the operation of the load balancing schemes implemented at the LM-Gateway connections. We hence assume that each sensor (fixed and mobile) sends their data to the closest LM.

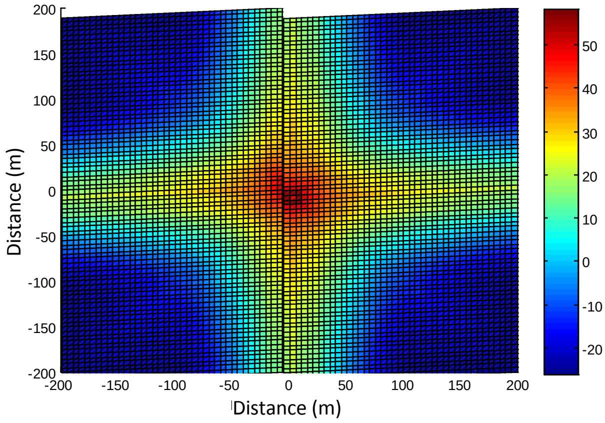
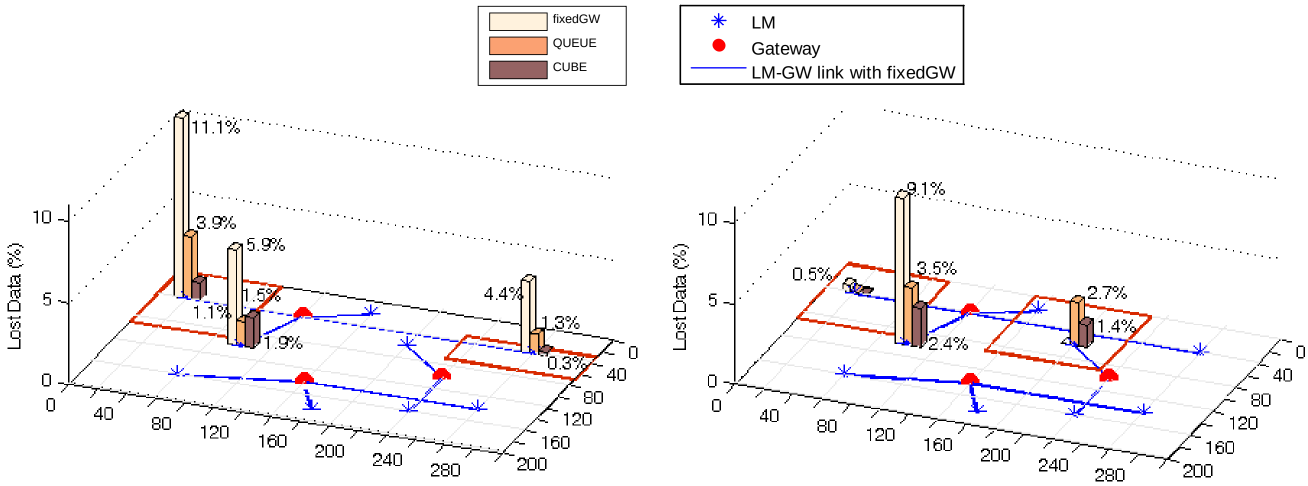


Figure 8. SNR maps for 802.11 transmissions in an industrial environment [20].

2.6 Performance analysis

Figure 9 depicts the percentage of lost packets for the two scenarios and the three policies under evaluation, i.e. a fixed assignment of LM to Gateway ('fixedGW' in Figure 9), and the QUEUE and CUBE schemes. The values are depicted only for those LMs that experienced a non-negligible number of errors. In particular, the results are depicted for LMs number 5, 6 and 8 in S1, and 5, 7 and 8 in S2. Their location in the industrial scenario is depicted in Figure 7. These LMs correspond to those deployed inside or close to the working areas specified in Figure 7 and in scenarios S1 and S2. These areas can concentrate a higher number of nodes during the execution of the tasks, and hence the network load increases.

The figure clearly shows that a fixed assignment of LM to Gateway nodes (fixedGW) results in the largest percentage of lost packets as fixed assignment cannot effectively cope with the spatio-temporal variations of the data. The implementation of load balancing schemes can better cope with such variations, and QUEUE and CUBE considerably reduce the percentage of lost packets in S1 and S2. CUBE outperforms QUEUE. For example, QUEUE reduces the percentage of packets lost with respect to fixedGW by 69% and 35% in S1 and S2 respectively, whereas CUBE reduces it by 85% and 57%. Different patterns are observed for S1 and S2. In S1, CUBE and QUEUE reduce the percentage of lost packets in all LMs compared to fixedGW. This is not the case in S2 where we can see that fixedGW actually achieves a lower percentage of lost packets in LM7 compared to CUBE and QUEUE. This better performance of fixedGW at LM7 is achieved at the expense of concentrating most of the packets lost in S2 at LM5. This is due to the fact that LM5, LM6, LM8 and LM9, in addition to both cameras, are connected to the same Gateway (Gateway 3) with fixedGW, and only LM2 and LM7 connect to Gateway 1. The concentration of mobile sensor nodes in areas B and C results in the overload of Gateway 3's channel. Since LM5 is the LM that higher amount of data received from sensors nodes in S2, the 9.1% of its packets are lost. To balance the load experienced by the different Gateways' channels, QUEUE and CUBE assign LM5 and LM6 to Gateway 1 during part of the time. As previously highlighted, both solutions reduce the total amount of lost packets, while also distribute losses between different LMs. The concentration of losses in an LM is very negative as LMs receive data sensed within the same area, so a very high percentage of lost packets in an LM result in that this LM will not be able to transmit the data collected in its serving area.

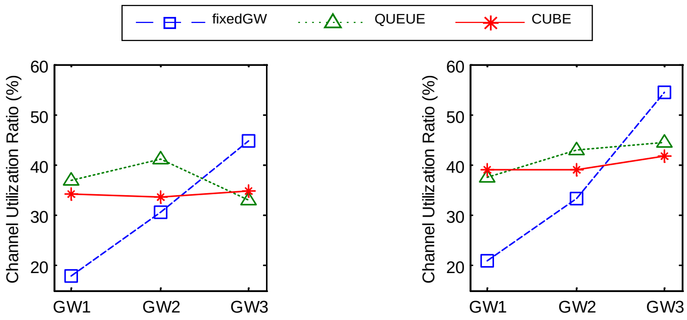


a) S1.

b) S2.

Figure 9. Percentage of packets lost.

CUBE outperforms QUEUE because it can better balance the load between Gateways. This is illustrated in Figure 10 that represents the average CUR (Channel Utilization Rate) across the channels in the three gateways deployed in the industrial scenario under evaluation. Figure 10 shows that CUBE is the scheme that better balances the load or CUR between the three gateways, which guarantees that none of them will be saturated and can hence support spatio-temporal variations of the data load within the industrial scenario.



a) S1. *b) S2.*

Figure 10. Average CUR experienced at the channels between LMs and Gateways.

Figure 11 shows the cumulative distribution function (CDF) of the number of times per second that each LM changes its serving Gateway. A LM changes its serving Gateway when requested by the load balancing scheme in order to balance the load among the Gateways in the scenario. Figure 11 clearly shows that CUBE demands significantly less changes of serving Gateway than QUEUE, and hence results in a more stable network operation. For example, when implementing CUBE, approximately 92% and 95% of LMs change their serving Gateway every 100 seconds or more (which is equivalent to changing 0.01 times per second the serving Gateway) in S1 and S2 respectively. On the other hand, when implementing QUEUE, only the 37% and 46% of LMs change their serving Gateway every 100 seconds or more, and approximately 10% and 30% of LMs change their serving Gateway every 5.8 seconds or less (which is equivalent to changing 0.17 times per second the serving Gateway) in S1 and S2 respectively. These results show that QUEUE significantly augments with respect to CUBE the frequency at which an LM changes its serving Gateway (or the number of times per second that an LM changes its serving Gateway). The conducted analysis has shown that QUEUE results in that the data queue at certain LMs is continuously close to the threshold QR_{th}. When such threshold is surpassed, QUEUE changes the serving Gateway to the corresponding LM. However, the scheme is not capable to achieve a network solution that ensures that the data queue of all LMs is below QR_{th}, which results in frequent and continuous requests to change the serving Gateway.

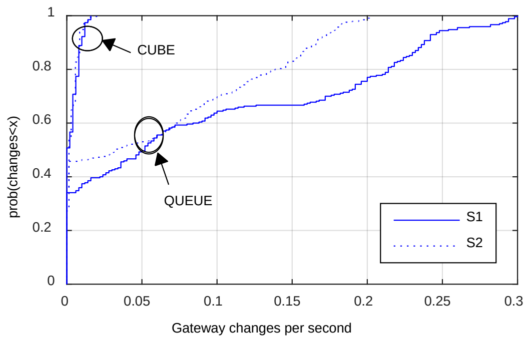
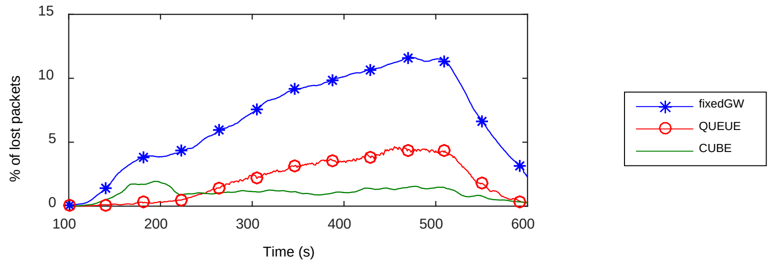
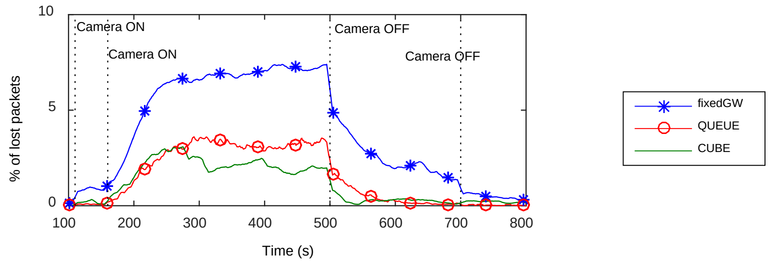


Figure 11. CDF of the number of times per second that each LM changes its serving Gateway.

Figure 12 represents the evolution of the percentage of packets lost as a function of the time. The time intervals represented in Figure 12 correspond to the time during which there are tasks executed in S1 and S2 in the working areas A, B and C. During these time intervals, the network load in these areas increases due to the mobility of nodes and the activation of high-bandwidth sensors in S2. Figure 12.a shows that, at the start of the time interval (i.e. when the network load has not yet significantly augmented), QUEUE slightly improves the packet loses with respect to CUBE. However, when the load increases with time (until *t=500*s, when the load starts decreasing), CUBE significantly outperforms QUEUE and reduces the percentage of lost packets. For example, during the interval [250s,500s], CUBE reduces the average percentage of lost packets with respect to QUEUE by 63%. In addition, it is important to remember that CUBE significantly reduces the number of times a LM must change its serving Gateway (Figure 11), and hence guarantees a more stable network operation. In S2, the network load rapidly increases in working areas B and C when the IP cameras area switched on at t=110s and t=160s (Figure 12.b). In particular, the network starts saturating when the two cameras are active (i.e. after t=160s), and the percentage of lost packets increases although CUBE and QUEUE significantly reduce this percentage with respect to a fixed assignment of LMs to Gateways. CUBE is again the scheme that results in the lowest percentage of lost packets (CUBE reduces the average percentage of lost packets with respect to QUEUE by 32% during the interval [250s,500s] in S2) and number of changes of serving Gateway.



a) S1.



b) S2.

Figure 12. Percentage of packets lost in the working areas in S1 and S2.

2.7 Summary

In this study within T2.3, we have proposed and evaluated a dynamic load balancing scheme for industrial wireless networks. The scheme has been designed with the objective to support the foreseen spatio-temporal variations of data in Industry 4.0. The proposed scheme balances the load among nodes taking into account the quality of the wireless links, the amount of data to be transmitted by each node and the congestion of wireless channels. All the information needed by the proposed scheme is easily available and measurable in wireless nodes. The scheme is capable to adapt the configuration of wireless links to the spatio-temporal variations of data in reconfigurable and dynamic industrial environments. These benefits are obtained while controlling the signaling overhead and reducing the number of times that the connections between wireless nodes has to be changed. The conducted evaluation has demonstrated that the proposed load balancing scheme significantly improves the reliability (by up to 85%) achieved in current deployments where wireless links between nodes are generally predefined and fixed. The proposed scheme also outperforms existing load balancing solutions that base their decision on the queue of data waiting to be transmitted by wireless nodes. In this case, our proposed scheme improves the reliability compared to queue-based load balancing scheme between 23% and 62% under the scenarios evaluated. These gains are obtained with a more stable network operation that significantly reduces the number of times nodes need to change their wireless links to support spatio-temporal variations of data in industrial environments.

3 Prototype for reliable industrial wireless communication

Within task T2.3, UMH has also been working on the development of a prototype demonstrating the capacity to provide reliable wireless communication between a mobile robot and a remote controller. This prototype has been designed to support the AUTOWARE use case and requirements of the Tekniker neutral experimentation infrastructure for intelligent automation applications (see deliverable D1.1 [9]). This facility (that will be presented in more detail in next subsections) is a standalone workcell deployed in an industrial shopfloor. It includes a dual-arm robot, a tool changer, interaction devices, and multiple sensors for safety and interaction. Within AUTOWARE, Tekniker is working on the evolution of its neutral facility to incorporate new solutions and technologies developed within AUTOWARE. Tekniker aims to improve the capabilities of its neutral facility to study and develop new techniques in collaborative robotics, and finally increase the capacity of industrial infrastructures to adapt to production demands and changes. In this context, one of the particular objectives of Tekniker is to incorporate into the neutral facility a mobile robotic platform that will act as a component supplier for the dual-arm robot. To ensure coordination and interoperability of these production resources – the dual-arm robot and the mobile robot–, a highly reliable communication between both robots is required (i.e. to guarantee that no data is lost and that data is received in time). In this context, we have developed a prototype to provide reliable wireless communication solutions exploiting diversity and redundancy. The developed prototype has been integrated and evaluated in the Tekniker neutral experimentation infrastructure. This first version of the deliverable D2.3 presents some initial results achieved in the field trials. A further analysis of the performance provided by the developed solutions will be presented in the second version of this deliverable.

3.1 Diversity and redundancy for wireless communications

Diversity can improve the reliability of wireless communication. 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 [31], which might affect the capacity to guarantee the deterministic latency requirements that generally characterize industrial applications [32]. An alternative is the use of redundant wireless communication. 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 [33]. This is confirmed by [33] 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 communication are analytical or simulation-based, with the exception of [34].

Considering the potential of using diversity and redundancy to improve the reliability and latency performance of wireless communication, we have developed a prototype that implements different diversity-based and redundancy-based solutions to provide a reliable industrial wireless communication between the dual-arm robot and the mobile robot integrated within the Tekniker neutral experimentation infrastructure. It is also important to highlight that, to the best of our knowledge, no study has previously analyzed experimentally the capacity of redundant wireless communication to support mobile industrial applications.

3.2 Tekniker neutral experimentation infrastructure for intelligent automation applications

The industrial wireless communication prototype has been integrated into the Tekniker neutral experimental infrastructure for intelligent automation applications for robotic industrial scenarios. This facility was presented in D1.1 [9]. The neutral experimentation infrastructure is a standalone workcell deployed in an industrial shopfloor (see Figure 13). It includes a dual-arm robot, a tool changer, interaction devices, and multiple sensors for safety and interaction. The workspace offers robotized mechanisms to implement now fully manual assembly processes as collaborative assembly. Tekniker is working on the integration of a mobile robot into the neutral facility that will act as a component supplier for the dual-arm robot (the mobile robot can be seen in Figure 13). Thanks to the coordination between the mobile robot and the dual-arm robot, it is expected to reduce stops due to the lack of material and finally augment production efficiency.

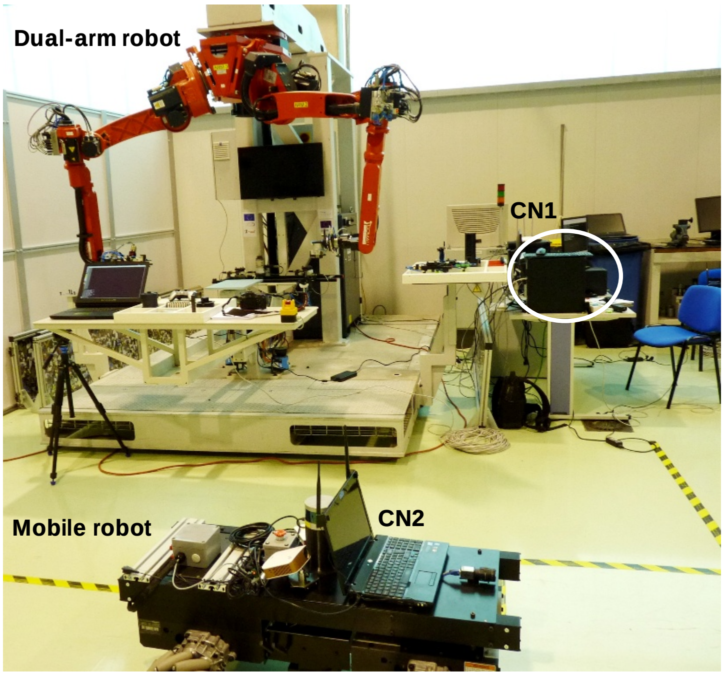


Figure 13. Tekniker neutral experimentation infrastructure for intelligent automation applications.

Coordination between the dual-arm robot and the mobile robot is performed through the exchange of commands and status reports between both robots (see Figure 14). The dual-arm robot requests a component to the mobile robot and indicates where this component is located through a movement command. The mobile robot calculates its own trajectory, and autonomously moves within the industrial shopfloor to collect the requested component and brings it to the dual-arm robot. The dual-arm robot continuously asks the mobile robot for its current 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. Due to the autonomous mobility of the mobile robot, it has been established that the complete process stops if communication fails. This fact highlights the importance of integrating a resilient industrial wireless communication network to support this type of industrial applications.

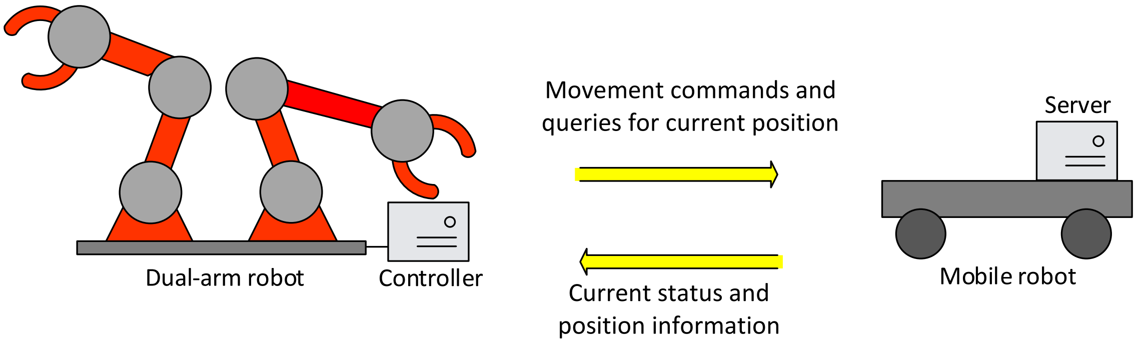
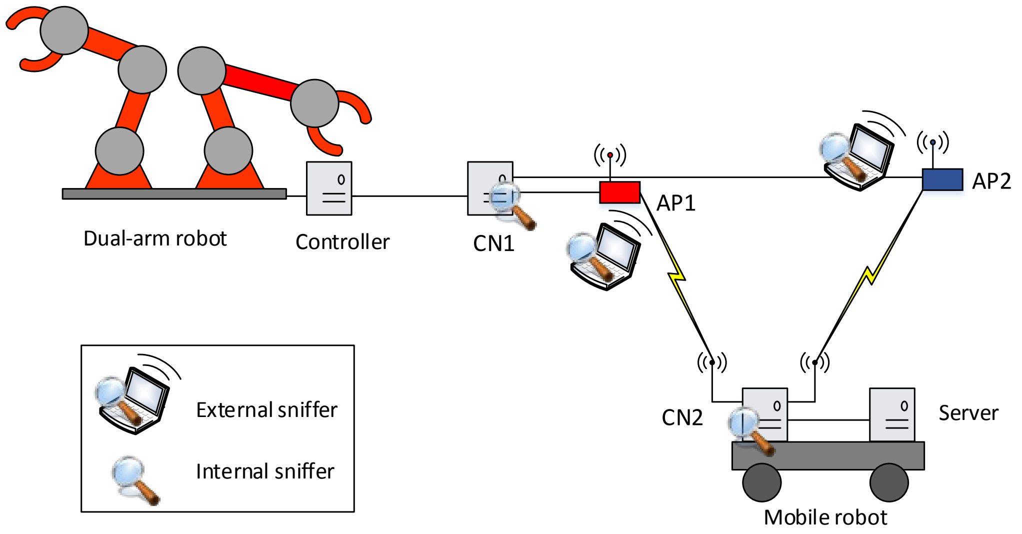


Figure 14. Bi-directional communication between the dual-arm robot and the mobile robot.

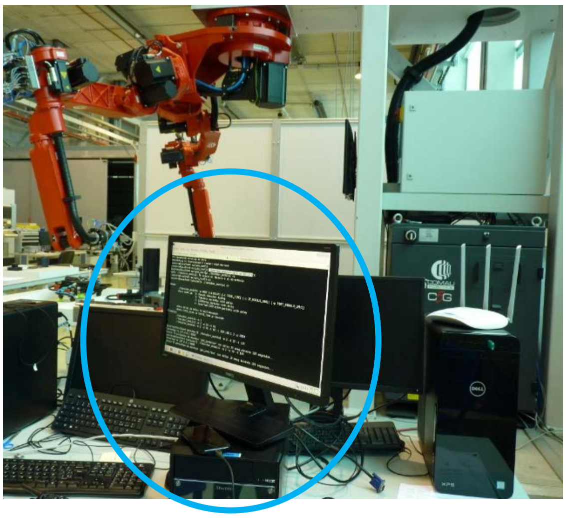
3.3 Reliable Industrial Wireless Communication

Figure 15 shows the prototype designed to ensure wireless resilient communication between the dual-arm robot and the mobile robot. The prototype establishes two independent wireless links between both robots, and data packets can be sent over both wireless links. The current implementation of the prototype uses IEEE 802.11 or WiFi for the wireless links. It is important to highlight that this solution is not restricted to this wireless technology, and others could be implemented in the prototype. The prototype is also ready to integrate heterogeneous wireless technologies.

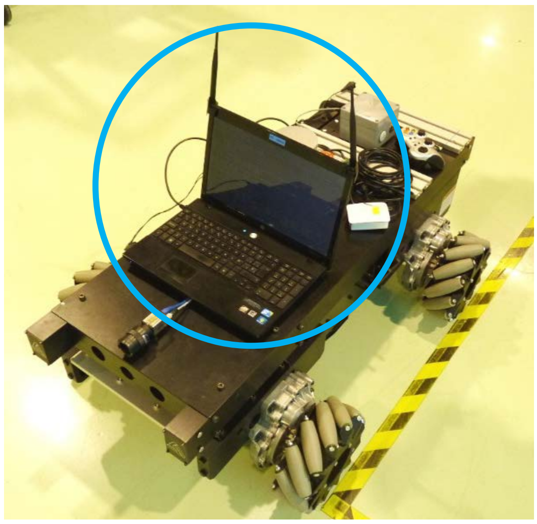
As shown in Figure 15.a, the dual-arm robot integrates a communication node (CN1) directly connected to the controller of the robot (wired connection), and to two WiFi APs identified as AP1 and AP2 in Figure 15.a. The mobile robot also integrates a communication node (CN2) that is directly connected to a server that is part of the mobile robot. The communication node in the mobile robot (CN2) incorporates two wireless interfaces to communicate simultaneously with the two APs. The communication nodes integrated within the collaborative robotics experimental facility (CN1 and CN2) are shown in Figure 15.b and Figure 15.c (these nodes can be also identified in Figure 13).



a) Schematic representation of the prototype.



b) Communication node 1 (CN1)



c) Communication node 2 (CN2)

Figure 15. Implemented prototype for reliable Industrial Wireless Communication.

CN1 and CN2 have been implemented in conventional computers 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. CN1 integrates an internal packet sniffer application developed by the UMH members to monitor the transmitted and received 802.3 packets sent to/from AP1 and AP2. The sniffer uses the open source <libpcap.h> library to extract information from the header of the packets. This information includes for example the source port, the destination port, the TCP (Transport Control Protocol) sequence number, the acknowledge (ACK) sequence number, and timestamp among others. 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 also integrates an internal packet sniffer application to monitor the transmitted and received 802.11 packets and hence be able to analyze the wireless performance. In this case, the sniffer extracts 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. 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 Figure 15.a).

The dual-arm robot and the mobile robot implement a TCP client-server application to exchange data packets using TCP sockets. The dual-arm robot controller establishes a TCP socket with CN1, and CN2 establishes a TCP socket with the TCP server at the mobile robot. To establish the end-to-end connection, CN1 has to establish a TCP socket with CN2. For the establishment of this communication, the developed prototype implements two different solutions exploiting diversity and redundancy respectively. Both solutions are presented below.

3.3.1 Solution 1: Wireless MultiPath TCP for reliable and low latency industrial wireless communication

This first solution aims at exploiting diversity to ensure a resilient, high reliable and low latency industrial wireless communication for mobile industrial applications. In this context, this solution is based on MultiPath TCP (MPTCP) [35]. MPTCP is an evolution of TCP that enables the simultaneous use of several IP-addresses/interfaces. MPTCP modifies TCP and provides a regular TCP interface to applications, while in fact spreading data across several subflows or communication paths [35]. A MPTCP connection is composed of one or more regular TCP subflows. Each TCP subflow is sent over a single communication path and is managed like a regular TCP connection (see Figure 16). Expected benefits of using MPTCP are better resource utilization, better throughput and smoother reaction to failures.

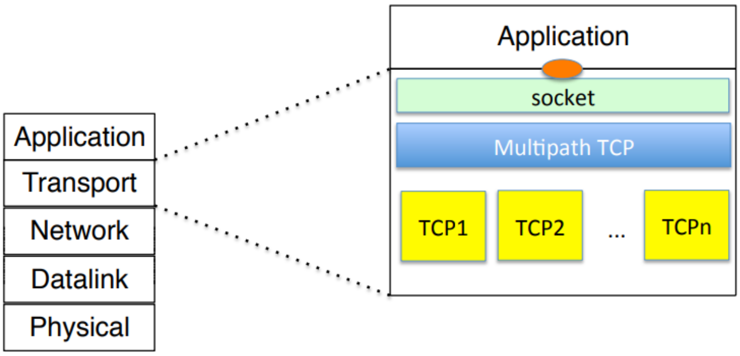


Figure 16. Architecture of MPTCP [36].

To exploit the availability of the two wireless connections between the dual-arm robot and the mobile robot, CN1 and CN2 incorporates the MPTCP Linux Kernel implementation developed by the IP Networking Lab of the Department of Computing Science and Engineering at Université Catholique de Louvain in Louvain-la-Neuve, Belgium [35], in particular version 2.5.2. MPTCP implements a scheduler that decides how data is sent through the different subflows. This MPTCP version provides two scheduler options. The default scheduler sends data on the subflow with the lowest RTT (Round-Trip delay Time). If the congestion window of the subflow with lowest RTT is full, the scheduler will start then transmitting on the subflow with the next higher RTT. There is also a second scheduler that sends data among the different subflows following a round-robin fashion, although its performance is worse. In this context, the default scheduler has been configured in the prototype.

To use MPTCP, only CN1 and CN2 are required to implement MPTCP. The use of MPTCP is transparent for the dual-arm robot and the mobile robot; the controller of the dual arm robot and the server of the mobile robot implement the conventional TCP protocol. To establish the end-to-end communication between the dual-arm robot and the mobile robot, CN1 establishes a TCP socket with CN2. Since CN1 and CN2 implement MPTCP, MPTCP detects two wireless links or paths between the communication nodes (through AP1 and AP2 respectively), and establishes two subflows to exchange data between them. When CN1 receives a data packet from the dual-arm robot, the packet is forwarded to CN2 through the wireless link with the lowest RTT (through AP1 or AP2). When CN2 receives a data packet from CN1, it forwards the packet to the server at the mobile robot. A similar process is followed for the data packets transmitted from the mobile robot to the dual-arm robot. This MPTCP-based solultion is represented in Figure 17.

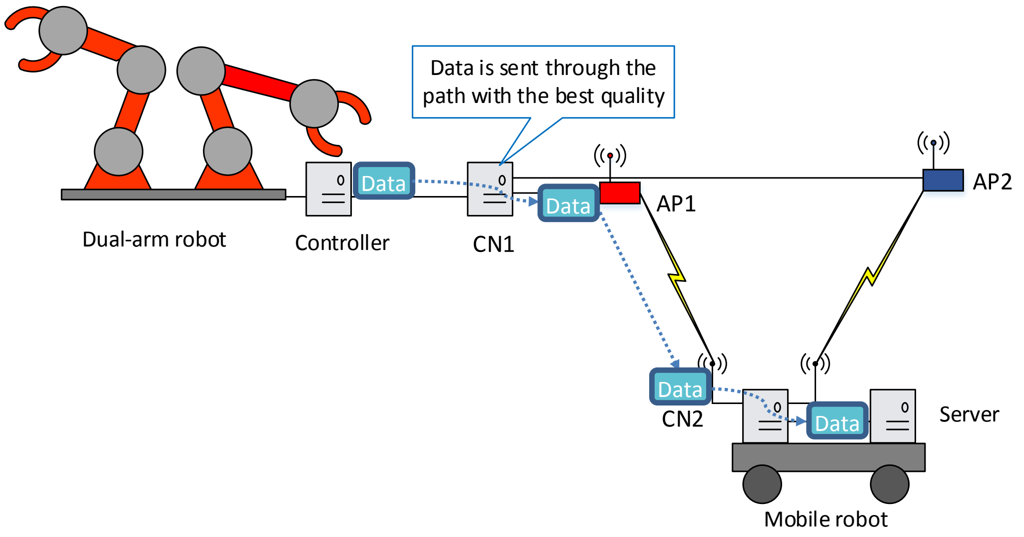


Figure 17. MultiPath TCP-based solution.

3.3.1 Solution 2: Redundancy for reliable and low latency industrial wireless communications

The developed prototype implements a second solution that exploits redundancy to achieve a reliable and low latency industrial wireless communication between the dual-arm robot and the mobile robot. While the previous solution chooses the wireless link with the best estimated quality to send data at each time, the redundancy-based solution sends duplicated data through both wireless link simultaneously. In this case, CN1 and CN2 use a Linux Kernel implementation without MPTCP, and this solution is implemented at the application layer, i.e., the communication nodes manage and process the exchanged data packets at the application layer. In this context, CN1 establishes two TCP sockets with CN2. One socket is established through AP1, and the other one through AP2. When CN1 receives data from the dual-arm robot controller, it 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. This redundancy-based solution is represented in Figure 18.

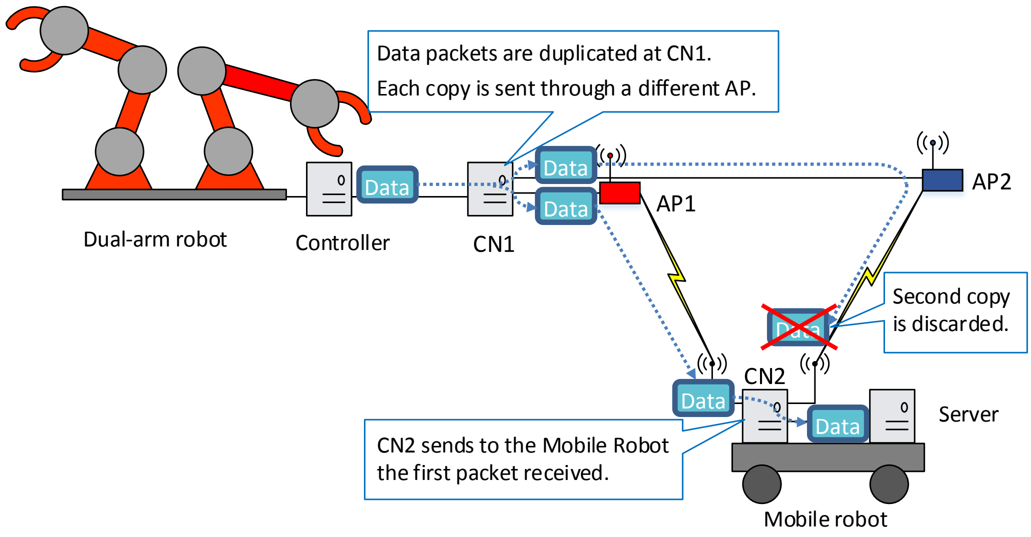


Figure 18. Redundancy-based solution.

3.4 Experimental trials

3.4.1 Scenario

Field trials have been conducted at the facilities of Tekniker to evaluate the different developed solutions. Figure 20 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 Figure 20). 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 Tekniker premises. The use of the 2.4GHz frequency band at the Tekniker premises is shown in Figure 19.

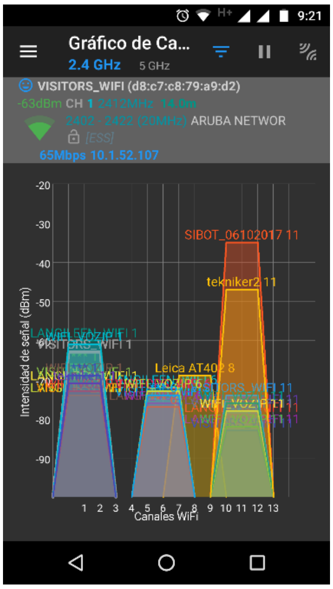


Figure 19. Use of WiFi channels by the different WiFi networks deployed in the Tekniker premises (captured with WiFiAnalyzer application).

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 Figure 20. 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 (Figure 20). 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 Figure 20. There is approximately 23 m 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. 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.

The robustness against disturbances and interferences of the implemented prototype has also been evaluated. To this end, we have introduced in the scenario an interference node, referred to as IN, that generates a constant interference signal on the same channel used by AP2 (WiFi channel 1). As shown in Figure 20, IN is located in the same room as the AP2, further than mark 6 at the end of the trajectory and around a corner. The picture of the IN is shown in Figure 21.a and the location where it is placed is shown in Figure 21.b. IN is implemented using an USRP (Universal Software Radio Peripheral) version 2 (USRP2). An USRP2 is a basic SDR (Software Defined Radio) platform, developed by Ettus Research, that implements the front-end functionality, and the Analog to Digital (A/D) and Digital to Analog (D/A) conversion on a FPGA. The physical layer processing is done on a PC where the USRP2 is plugged. The USRP2 connects to the PC through a Gigabit Ethernet interface. To generate the interference signal we used the GNU Radio toolkit, which is a free collection of signal processing blocks used for building SDR platforms. The flow-graph implemented in GNU Radio to generate the interference signal is shown in Figure 22.a. Figure 22.b shows the spectrum of the interference signal. The interference signal is centered in frequency 2.412 GHz (center frequency of channel 1 of IEEE 802.11 used by AP2) with a bandwidth (sampling rate in the flow-graph of Figure 22.a) of 20 MHz. Although a 20 MHz bandwidth was established, the spectral mask expands beyond the established bandwidth as shown in Figure 22.b. It is important to highlight that the interference generated over AP1 is negligible; AP1 transmits on channel 11 centered on 2.462 GHz.

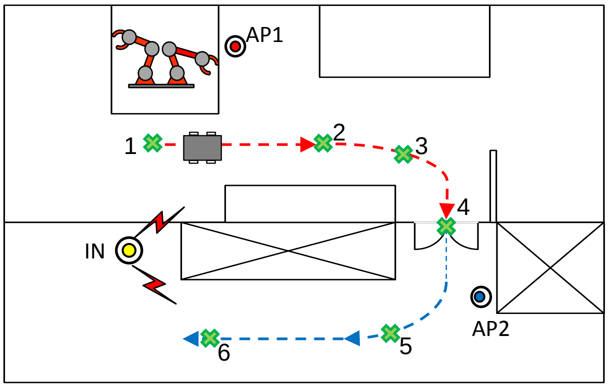
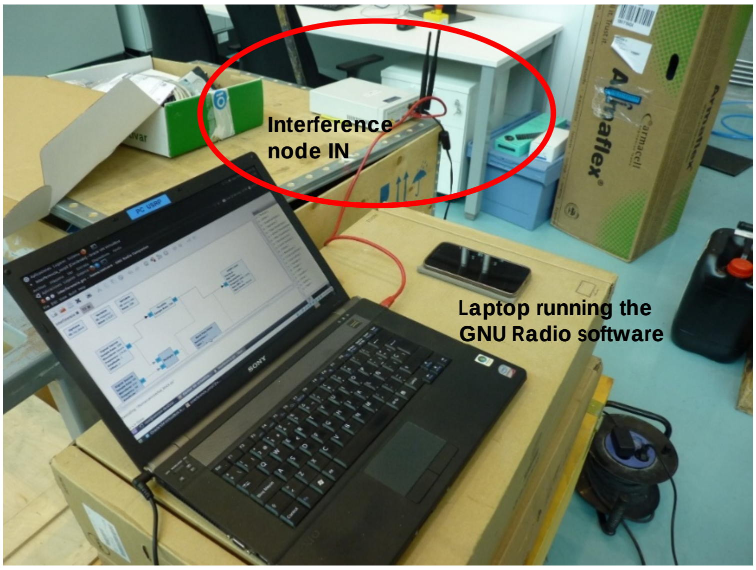
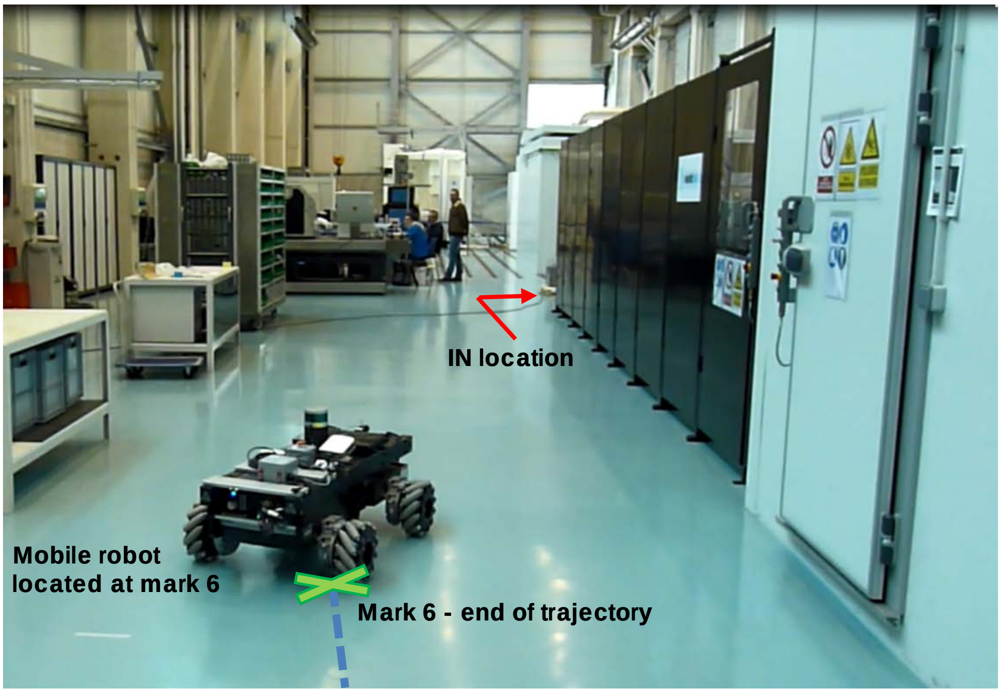


Figure 20. Simplified floor plan of the industrial shopfloor.

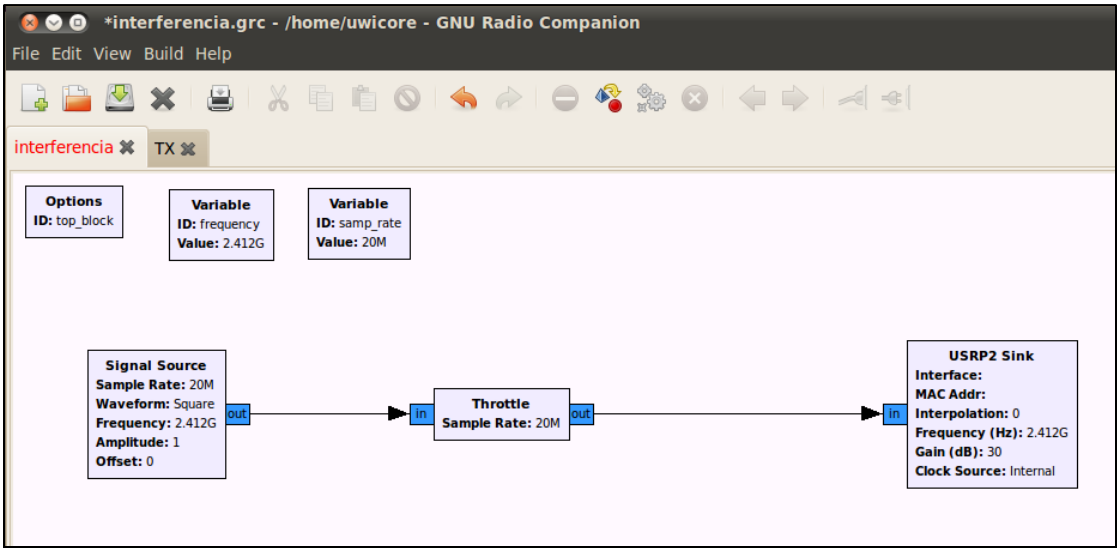


a) Interference node.

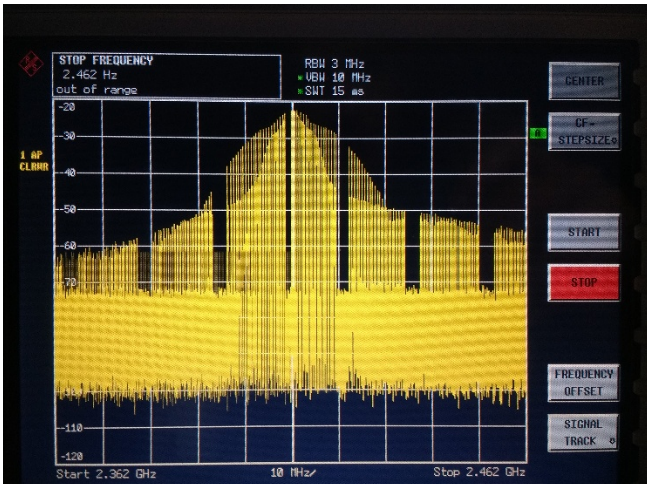


b) Location of the interference source IN in the Tekniker facilities.

Figure 21. Interference node deployed in the experimental scenario.



a) *GNU Radio flow-graph used to generate the interference signal.*



b) *Spectrum of the interference signal.*

Figure 22. Interference signal.

3.4.2 Reliability for industrial mobile applications

For each tested solution, several field trials have been conducted at Tekniker premises. Results are shown for specific trials although same trends have been found in all trials carried out for the same solution under the same scenario.

First, we have evaluated the performance achieved with the MPTCP-based solution and the redundant wireless solution when the mobile robot moves following the trajectory presented in section 3.4.1 (without incorporating the interference node). In this trials, AP1 and AP2 power levels are set to low and middle respectively. Figure 24 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. Figure 25 shows an example of the performance obtained when the MPTCP-based solution is used. 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 Figure 20 and to come back to its initial location at mark 1. Figure 24 and Figure 25 represent the wireless performance at the mobile robot although the wireless links between both robots are bidirectional. Figure 24.a represents the RSSI of the packets received at CN2 (attached to the mobile robot) from AP1 and AP2. Figure 24.b represents the data rate used for transmitting the packets received from each AP. Figure 24.c represents the PER experienced at CN2 over the wireless links with AP1 and AP2. Figure 24.d-f 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. Figure 24.d and Figure 24.e represent the latency experienced in the transmissions from AP1 and AP2 respectively. Figure 24.f 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 (different colors are used to identify the AP), and the latency is computed considering the first copy of a packet that is received through either of the two wireless links. Figure 25.a-c shows the same results as Figure 24.a-c, but for the case when MPTCP-based solution is applied. Figure 25.d shows the end-to-end latency between CN1 and CN2 experienced by the data packets similarly to Figure 24.f; in this case, packets are only transmitted through an AP.

Before analyzing the achieved results, it is important to highlight that the values achieved for a given performance indicator parameter in different trials cannot be compared in absolute terms since the particular values achieved in a trial at a given time depends on several factors that change at each trial and that cannot be controlled. For example, Figure 24.f and Figure 25.d show that the average latency experienced with both solutions (the MPTCP-based solution and the redundant wireless communication solution) respectively differ significantly: an average latency equal to 387ms is experienced with the MPTCP-based solution while only 123ms is experienced with the redundant solution. Different factors can affect the performance achieved at different trials. For example, as presented in Section 3.4.1, these trials were carried out at Tekniker premises at working hours. The two APs operated in the 2.4GHz band, and then coexisted with the permanent 2.4GHz wireless networks available at Tekniker (see Figure 19). The amount of traffic managed at the Tekniker wifi networks then affects the end-to-end latency experienced in the communication between both robots; higher traffic in the Tekniker network carries higher congestion levels and then higher waiting time to access to the channel. This is a factor that can change at different times and in different trials, and that is not under our control. In addition, it is important to highlight that the end-to-end latency also includes processing times at the transmitter and the receiver. In this context, we have observed in general higher end-to-end latency values for the MPTCP-based solution, as shown in Figure 23. Figure 23 depicts the CDF of the end-to-end latency experienced in all the trials evaluating the MPTCP-based solution and the redundant wireless communication solution respectively. This result reveals higher processing times in the transmitter and the receiver when the MPTCP protocol is used. In this context, we will analyze the performance provided with each solution in terms of general trends and without taking into account absolute values.

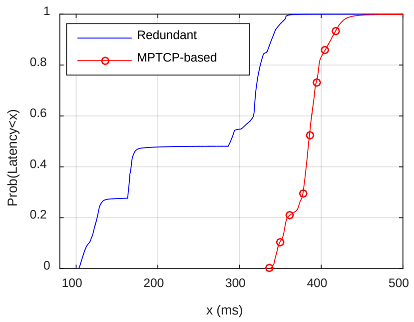


Figure 23. CDF of the latency experienced with the redundant wireless communications solution and MPTCP-based solution in all trials.

Figure 24 and Figure 25 demonstrate the benefits of introducing diversity and redundancy in industrial wireless communication. Figure 24 shows that when the mobile robot is in between marks 4 and 6 (Figure 20), the wireless link between AP1 and the mobile robot experiences harsh propagation conditions that significantly reduce the RSSI (Figure 24.a). Although AP1 adapts the transmission mode to use more robust ones with lower data rates (Figure 24.b), these low RSSI values result in an increase of the PER experienced in the link (Figure 24.c). From t=85s to t=190s, the mobile robot even loses the connection with AP1 (link outage); the connection with AP1 is re-established again at t=190s. These harsh propagation conditions also result in that 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[7]. In addition, during the link outage, 36% of the packets sent through AP1 do not reach the destination (packets are lost due to the

[7] 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.

overflow of the transmitter's buffer). As shown in Figure 24 and Figure 25, both solutions improve the resiliency of industrial wireless communications since the end-to-end connection is not compromised when the redundant wireless communications solution or the MPTCP-based solutions are applied. During the link outage with AP1, the dual-arm and mobile robots can still communicate through AP2.

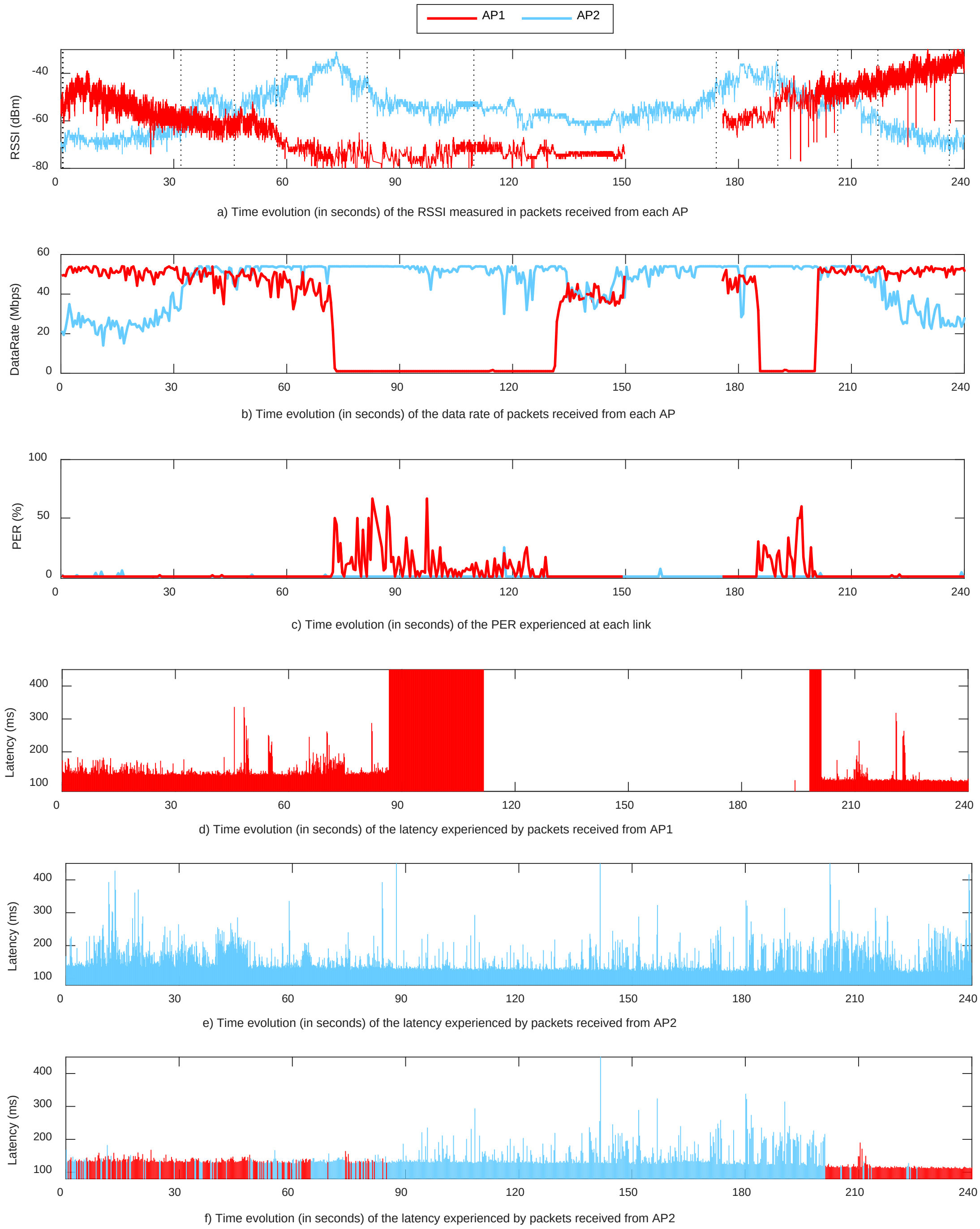


Figure 24. Performance achieved with the redundant communications solution.

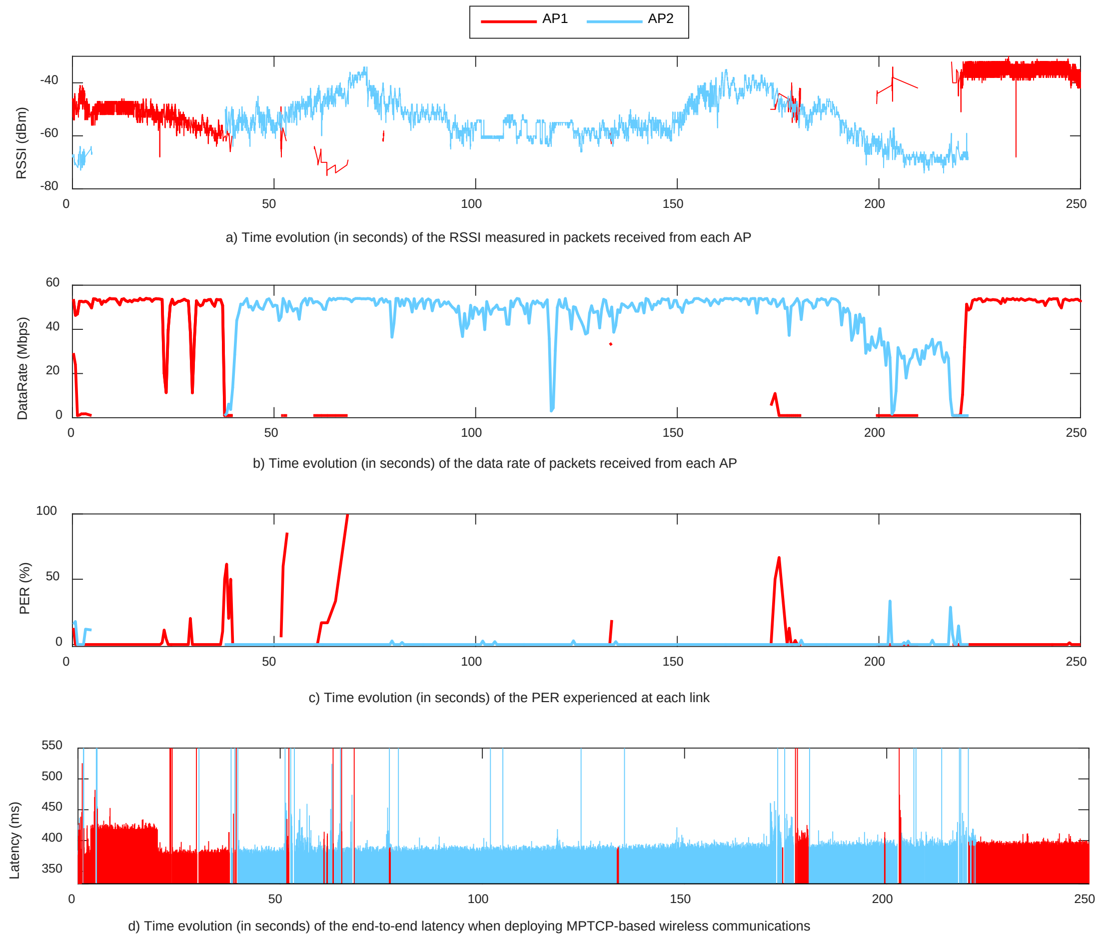
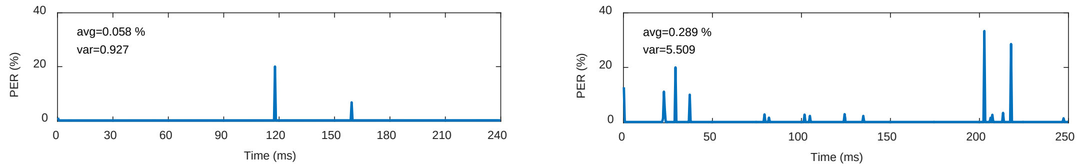


Figure 25. Performance achieved with the MPTCP-based solution.

Diversity and redundancy allow to increase the reliability of the communication between both robots. The MPTCP-based solution exploits diversity and sends packets through the AP that provides the highest estimated performance. As a result, the MPTCP-based solution guarantees low PER levels during the whole trajectory (Figure 25.c) guaranteeing a reliable end-to-end communication. The redundant wireless communication solution also achieves similar results in terms of reliability (Figure 24.c). In this case, duplicated copies of a packet are sent simultaneously through both APs. Then, the PER achieved in the end-to-end communication can be considered as the minimum of the two links at each time. This results in a reliable communication link that experiences very low PER values. Figure 26 shows the final end-to-end PER experienced at the communication link between the dual-arm robot and the mobile robot with both solutions (it is important to highlight that the results achieved with both solutions cannot be directly compared in terms of absolute values since they correspond to different trials but conclusions can be extracted comparing general trends). The results depicted in Figure 26 show that the redundant wireless communication solution better combats the high variability of radio propagation in harsh industrial environments, and minimizes the variability of the PER experienced in the channel. This is due to the fact that the redundant solution provides the receiver with the possibility to select on a per-packet basis the wireless link that experiences the best communication conditions. In the case of the MPTCP-based solution, the transmitter is the one that selects the channel with the best estimated communication conditions in a higher time scale.

This conclusion can also be reached when the end-to-end latency experienced with each solution is analyzed. For example, Figure 24 shows that 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 conditions with AP2, the RSSI received from AP2 is low (Figure 24.a) and the variability of the latency experienced by the packets sent through AP2 increases (Figure 24.e). 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 (Figure 24.d). In this context, most of the packets received at the mobile robot are those sent through AP1 (as indicated by the red color predominant in this period in Figure 24.f). However, a significant percentage of packets are still received through AP2, as shown in Figure 27.a that depicts the percentage of packets that are received at the mobile robot through each APs as a function of time. The results show that the redundant solution better exploits the availability of both wireless links, and is able to select the link with higher communication conditions in a very short time scale (in a per-packet basis). This allow to combat the high variability of the channel conditions, 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 136s when transmitted through AP1[8] and AP2 respectively (see Figure 28 that depicts the CDF of the end-to-end delay experienced through each AP and when used the redundant wireless communications solutions). This percentage is reduced to 3.9% with redundancy. However, the MPTCP-based solution is not able to adapt to the fast variability of the channel conditions as quick as the redundant solution does. As shown in Figure 27, all packets are sent through an AP or the other at a given point in time with the MPTCP-based solution.

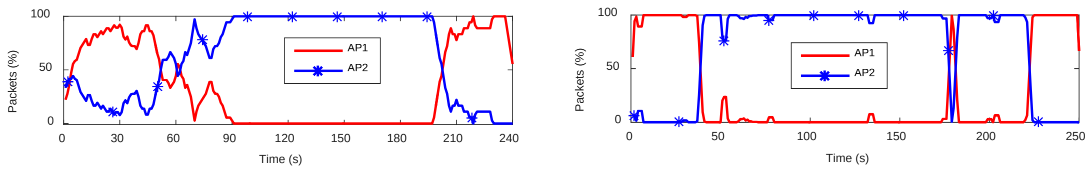
[8] 36% of the packets are actually lost through AP1.



a) Redundant wireless communications solution

b) MPTCP-based solution

Figure 26. End-to-end PER experienced at the communication link between the dual-arm robot and the mobile robot.



a) Redundant wireless communications solution

b) MPTCP-based solution

Figure 27. Percentage of packets sent through each AP.

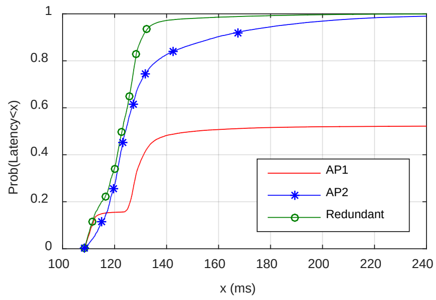


Figure 28. CDF of the latency experienced with the redundant wireless communications solution.

3.4.3 Robustnest against interference of redundant industrial wireless communication

In the previous section, it has been demonstrated that diversity and redundancy considerably improve the communication performance in terms of reliability and latency for mobile industrial applications when compared with the use of a single communication link. Redundancy even outperforms the diversity-based solution. By exploiting redundancy, it is possible to achieve a high reliable communication link (PER values close to zero among all the trajectory) with the lowest latency possible considering the two available wireless links; the redundant solution allows to select on a per-packet basis the wireless link that experiences the best communication conditions. In this context, in this section we focus on evaluating the robustnest against interference of the redundant industrial wireless communication solution. To this end, we also considered the scenario presented in Section 3.4.1 when an interference node IN is introduced, as shown in Figure 20. In this trial, we evaluate the performance achieved with the redundant solution when a node generates interferences on the link that experienced the best communication solutions (see Figure 29). In this trial, the mobile robot follows the trajectory depicted in Figure 20. IN starts to generate interference on the same channel than AP2 when the mobile robot is in between marks 5 and 6 (IN is turned on between t=69s and t=110s approximately). In this trial, AP1 transmission power has been set to middle level to guarantee that the connection between the mobile robot and the AP1 is not interrupted.

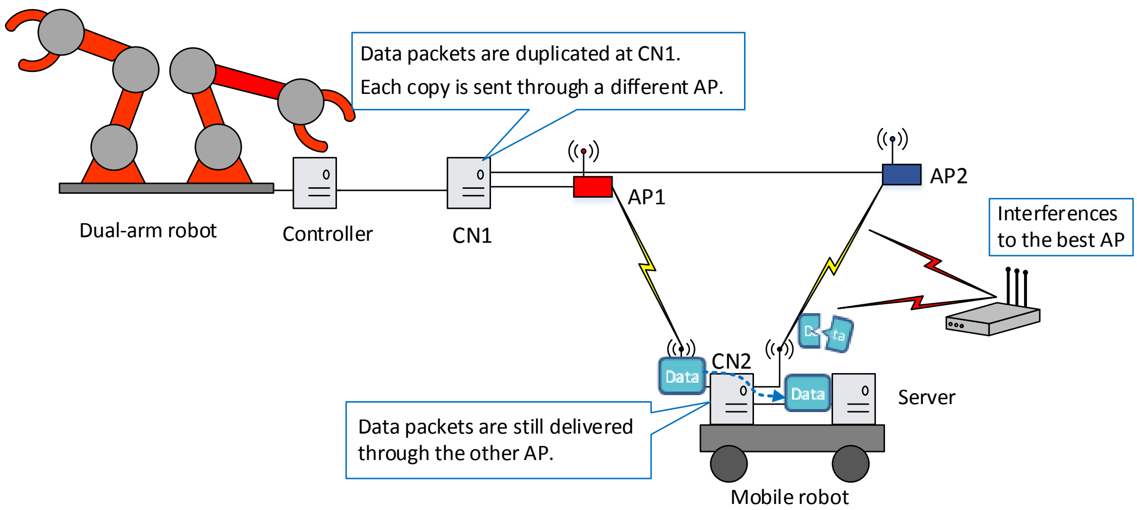


Figure 29. Evaluation scenario with interference node.

Figure 30 shows the performance achieved with redundant wireless communicationwhen there are interferences in the environment. The results show that when the mobile robot is in between marks 1 and 5, and IN is not generating interference, the performance achieved is similar to that shown in Section 3.4.2. When the mobile robot is moving between marks 4 and 5, the signal level from AP1 decreases and the signal level from AP2 increases, and the percentage of packets received through AP2 at the mobile robot increases (as shown in Figure 31.a). When the mobile robot is between marks 5 and 6, IN generates interference to AP2. Figure 30.a shows that although the signal level received at the mobile robot from AP2 is good (and better than from AP1), AP2 adapts its transmission data rate (Figure 30.b) to try to maintain low PER values, but, still, the PER experienced in the wireless link with the AP2 increases due to the interference received from IN (Figure 30.c). In addition, latency experienced by the packets sent through AP2 also increases considerably as shown in Figure 30.e, and some packets experienced latency values higher than 1.8s. Thanks to the use of redundant wireless communication, it is possible to maintain a robust reliable communication between both robots even under the presence of interference sources. As shown in Figure 31.b, the redundant solution maintained low PER values even when the mobile robot was in proximity of the IN node. When the IN causes interferences to AP2, most of packets are received at the mobile robot through AP1 as shown in Figure 31.a, despite the fact that the signal level received from AP2 is higher than that received from AP1. It is important to highlight that when the IN is turned on, the WiFi networks deployed in the Tekniker premises also are affected by the interferences. The different networks operating in channel 1, and also those operating in channel 6, change to channel 11, the channel that is less affected by the interferer; Figure 32 shows the use of the WiFi channels when the IN is turned on. This fact also affects the performance experienced at the wireless link established with AP1 (AP1 operates in channel 11) since a higher congestion is then experienced in this channel. However, the redundant solution exploits the variability of the radio channel and some packets are still received from AP2, those experiencing lower end-to-end latency. As Figure 30.f shows, the redundant wireless communication solution finally achieves an end-to-end latency lower than that achieved through each wireless link separately, even in the time period when IN interferes AP2. The redundant wireless communication solutions provide a robust and reliable communication that allow to maintain low latency values, even under the presence of interferences.

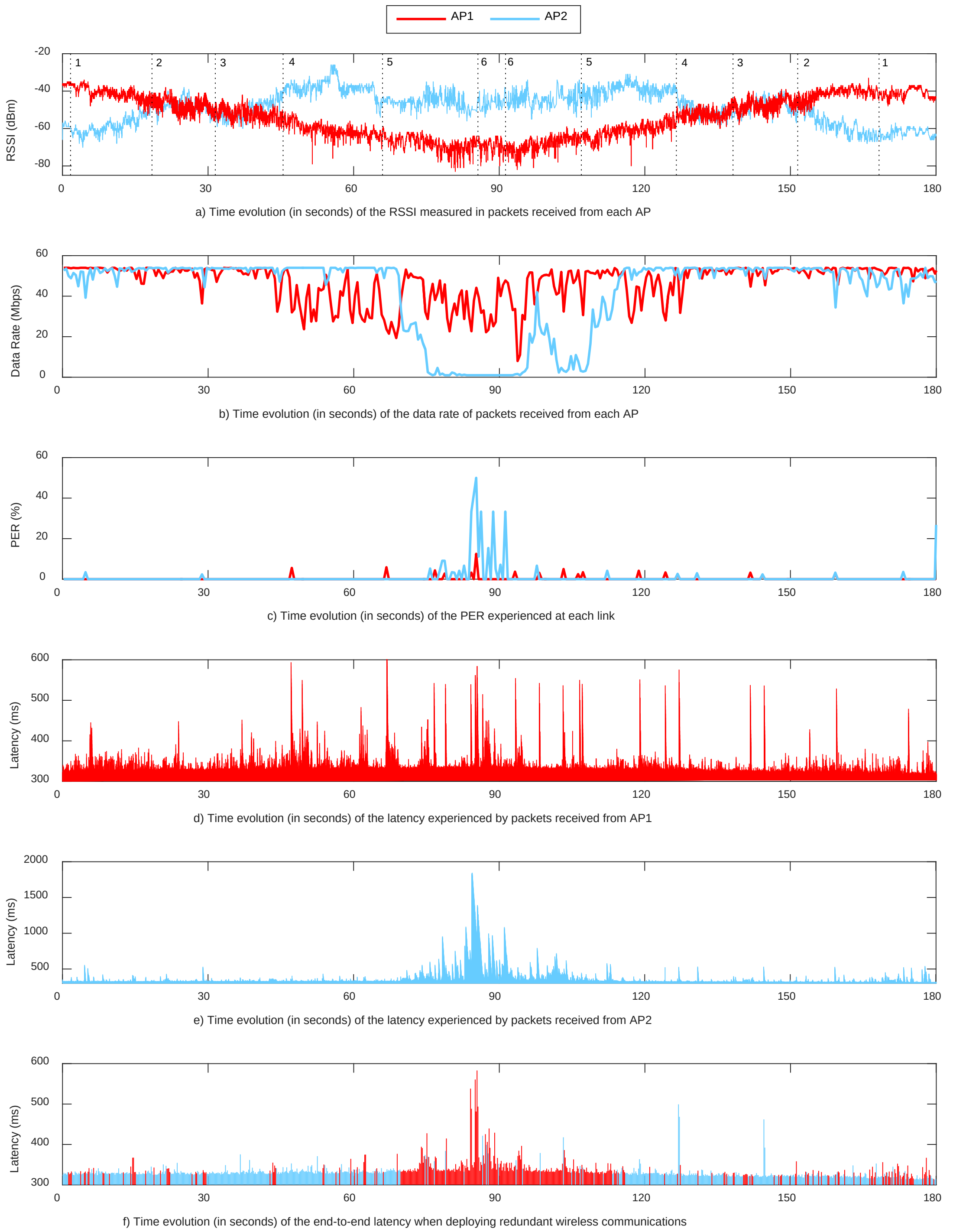
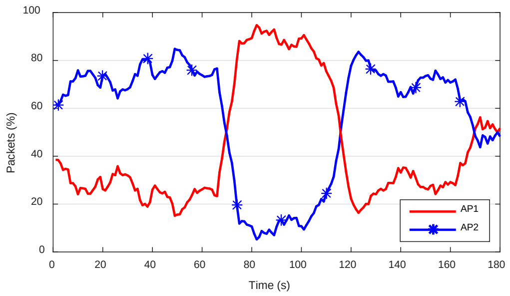
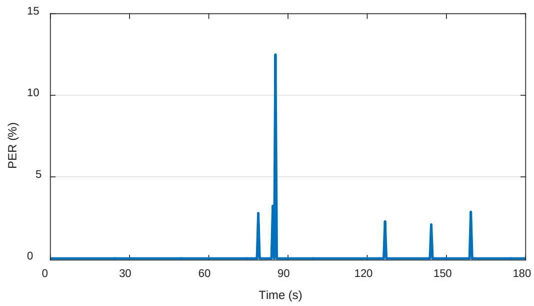


Figure 30. Performance achieved with the redundant wireless communications in the scenario with interferences.



a) Percentage of packets received at the mobile robot through each AP.



b) End-to-end PER.

Figure 31. End-to-end PER experienced at the communicatin link between the dual-arm robot and the mobile robot in the scenario with interferences.

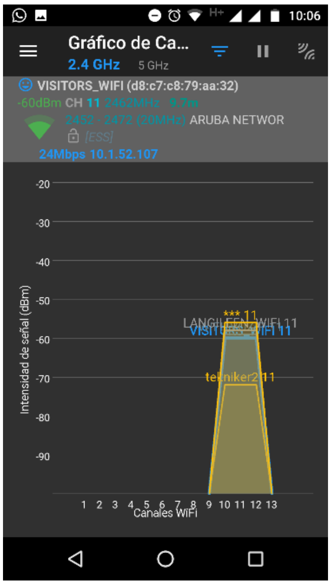


Figure 32. Use of WiFi channels by the different WiFi networks deployed in the Tekniker premises when interference are generated on channel 1 (captured with WiFiAnalyzer application).

3.5 Summary

This study carried out within T2.3 has experimentally analyzed for the first time the capacity of redundant wireless communication to support mobile industrial applications. A prototype has been implemented. The prototype has been designed to support resilient wireless communication between a mobile robot and a fixed dual-arm robot in the Tekniker neutral experimentation infrastructure for intelligent automation applications. The prototype has been evaluated through experimental trials carried out in the Tekniker premises. The conducted experiments have shown that diversity and redundancy can help overcome some of the limitations traditionally affecting wireless communication in harsh industrial environments (e.g. link outages), and improve the reliability and latency of industrial wireless communication. By exploiting redundancy it is possible to further improve the performance of end-to-end communication links and to deal with the high variability of radio propagation in harsh industrial environments.

4 Priority-based Grant-free Scheduling for Deterministic Industrial 5G Communication

3GPP technologies are constantly evolving through Generations of commercial cellular/mobile systems. Over the last years, much attention has been paid to improving capacity and data rates provided by 3GPP standards. With eight-layer multiple-input multiple-output (MIMO) transmission defined in Release 10 and carrier aggregation of up to 32 carriers introduced in Release 13, the LTE peak data rate can already go up to ~25 Gb/s [37]. Diverse services and use cases are arising in new areas demanding new communication requirements that pose challenges on existing 4G LTE systems, and claim for a new 5G generation. For example, closed-loop control applications in industrial factory automation demands very low end-to-end delays (~1ms) and very high reliability levels (99,9999999 %) [38], while smart cities demand connectivity for a very high number of nodes transmitting very low amounts of data. In this context, 5G networks will have to meet diversified communication requirements demanded by very different services. The International Telecommunication Union (ITU) classifies the 5G mobile network services into three different categories [39]: Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (URLLC), and Massive Machine Type Communications (mMTC). Each of these services claims for very different communication requirements in terms of data rates, reliability, latency, number of connected nodes, etc. (see Figure 33). For example, eMBBs aims to meet the people's demand for an increasingly digital lifestyle, and focuses on services that have high requirements for bandwidth, such as high definition (HD) videos, virtual reality (VR), and augmented reality (AR). URRLC implies fulfilling very tough requirements on reliability, availability, and latency in order to offer connectivity that is essentially always available. Examples include health applications, traffic safety and control, control of critical infrastructures, and connectivity for industrial processes. mMTC addresses applications with a very large number of sensors, actuators, and similar devices typically associated with little traffic as well as requirements on low device cost and very long battery life [37].

5G networks are envisioned as a promising key enabler for the Factories of the Future. As highlighted in [6], 5G networks will provide the unified communication platform needed to disrupt with new business models and to overcome the shortcomings of current communication technologies. However, the deployment of connected factories under the paradigm of Industry 4.0 requires supporting URLLC wireless communication [38]. To achieve this, enhancements are still necessary within 3GPP standards [40].

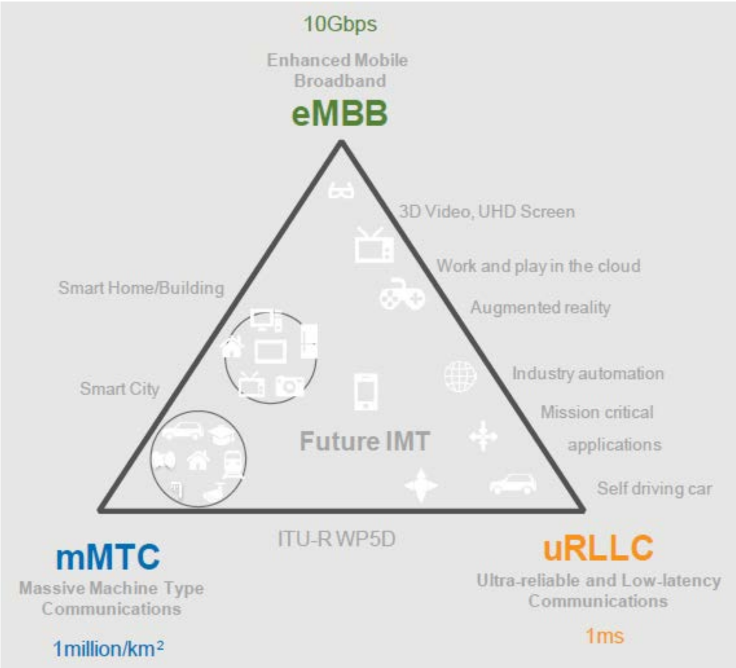


Figure 33. 5G mobile network services and requirements [41].

4.1 State of the art

The LTE link layer has not been designed to address latency-critical communication requirements. Latency reduction is currently being considered in 3GPP, and several proposals are being studied. As presented in [21], the use of shorter Transmission Time Intervals (TTI), and other coding schemes to also short the processing times are being studied for latency reduction in 3GPP standards. However, physical layer and medium access mechanisms are major contributors to the total end-to-end delay for transmissions. For example, in the LTE scheduling scheme for uplink transmissions (see Figure 34), the UE (User Equipment) has to send a Scheduling Request (SR) to the eNB (enhanced Node B). After receiving this SR, the eNB sends a scheduling grant to the UE. In this grant message, the eNB indicates the schedule and the resources to be used by the UE. When the grant message is received, the UE can then transmit its data. This process before starting any transmission already results in an average delay of 9.5ms.

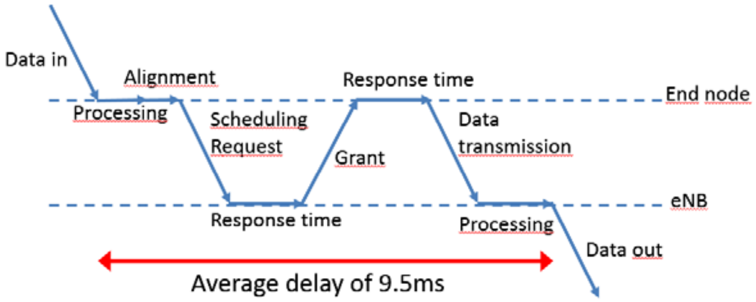


Figure 34. LTE scheduling for uplink transmissions.

To reduce such delay, Release 14 also incorporates a Semi-Persistent Scheduling (SPS) scheme [42]. With SPS, dedicated resources are assigned to UEs and then it does not require UEs to request resources for their uplink (UL) data transmissions. However, limitations arise when the traffic arrival is uncertain or aperiodic. In this case, reserving resources might be highly inefficient since many of them might be under-utilized [43]. Grant free transmission is being studied for URLLC under Release 15 [44]. With grant free transmissions, eNB allocates contention-based resources that are shared by a group of UEs. In this case, collisions can happen when more than one UE try to transmit/retransmit data in the same resource. The performance loss due to collisions can be overcome with additional retransmissions, but it also introduces additional delays that can compromise the stringent latency/timeliness requirements.

Some work is available in the literature addressing this topic. For example, authors of [45] propose to maintain dedicated resources for each initial UE transmission. For retransmissions, a pre-scheduled resource is established to this end which is shared by a group of UE. In [45], the optimum number of UEs sharing the same pre-scheduled resource for retransmission is calculated based on the quality of the channel and the traffic generated by each UE. This work shows that with the right dimensioning of groups, the communication requirements of UEs can be satisfied while improving the resource efficiency when compared with the tranditional SPS scheme. On the other hand, the performance of grant-free scheduling schemes for uplink communications has been evaluated in [46]. In this work, authors showed that collision probability decreases if UEs sharing the same resources can be split in smaller groups. In addition, [46] also demonstrated that sending several consecutive repetitions of the same packet can be used to increase the probability of correct reception and comply with the communication requirements of URLLC in terms of reliability and latency/determinism. The benefits of transmitting multiple copies of the same data packet in consecutive TTIs to increase the probability of correct reception is also shown in [47]. In this work, authors calculate the optimal number of repetitions to achieve the required reliability level within the stringent deterministic latency requirements. Authors of [47] also propose to randomly chosen the resource to use in each repetition from the available resources with the aim of reducing the overall collision probability. Repetitions improve the successful reception rate at the expense of a higher use of radio resources that sometimes can be unnecessary (if first transmission is correctly received). In this context, further research is then required in this area to efficiently meet the communication requirements of deterministic communication.

4.2 Grant-free scheduling based on prioritized contention resolution and local channel sensing

Within T2.3, we are currently working on the development of a new scheduling solution for 5G standard. The proposed scheduling scheme aims to achieve the communication performance required by industrial communication in terms of latency/determinism and reliability, among others. In this study, we focus on studying a grant-free scheduling scheme for traffic with uncertain or aperiodic arrivals. In this context, a shared radio resource is assigned periodically to a group of UEs. If more than one UE want to transmit in the next shared resource, collisions can happen. To avoid collisions among UEs sharing the same radio resources, the designed scheduling scheme is based on the transmission of announcement (AN) signals and local channel sensing.

The proposed scheduling scheme establishes that UEs that want to transmit data in the next shared resource have to previously transmit AN signals and sense the channel in slots dedicated to this aim. As shown in Figure 35, the slots dedicated to the transmission of the AN signals (referred to as announcement slots or AN slots) are located previously to the shared resource. The AN signals will be transmitted in radio resources with a shorter length (in time) than the resources used to transmit data with the aim of increasing radio resource utilization efficiency. The definition of short TTIs is being carried out in 3GPP Rel. 15 and Rel. 16 for latency reduction [48], and more information about short TTIs will be given in Section 4.2.1. The transmission of the AN signals by the UEs sharing the same radio resource is organized based on pre-established priorities in a way that lower priority UEs can sense if higher priority UEs want to transmit in the next shared resource. If this is the case, lower priority UEs will postpone its transmission. Figure 36 illustrates this priority-based AN signals transmission and channel sensing process. In the example depicted in Figure 36, three AN slots are configured to manage the access to the shared resource of eight UEs. When a UE wants to transmit in the following shared resource, it has to transmit AN signals in the blue slots and sense the channel in the orange slots according to its priority. For example, UE4 wants to transmit data in the next shared resource. In this case, UE4 has to transmit an announcement signal in the first AN slot. If other lower priority UEs also want to transmit in the next shared resource, they will sense the channel in the first AN slot and will sense the channel as busy. Then, UEs with lower priority than UE4 will postpone their transmissions. UE4 also has to sense the channel on second and third AN slots. If the channel is sensed as busy in the second or third AN slot, UE4 will postpone its transmission since a higher priority UE aims to transmit in the next shared resource. In other case, UE4 will transmit data in the next shared resource.

As previously mentioned, we are currently working on the definition and evaluation of this grant-free scheduling scheme. Some technical aspects still need to be carefully designed, such as the identification of the required number of announcement slots, the identification of the UEs that will share the same radio resources, and the management of the UEs priorities. Additional details are provided in next subsections.

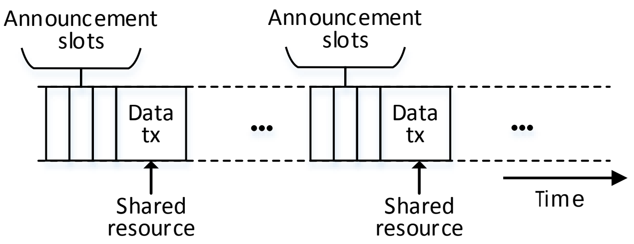


Figure 35. Announcements slots for contention resolution.

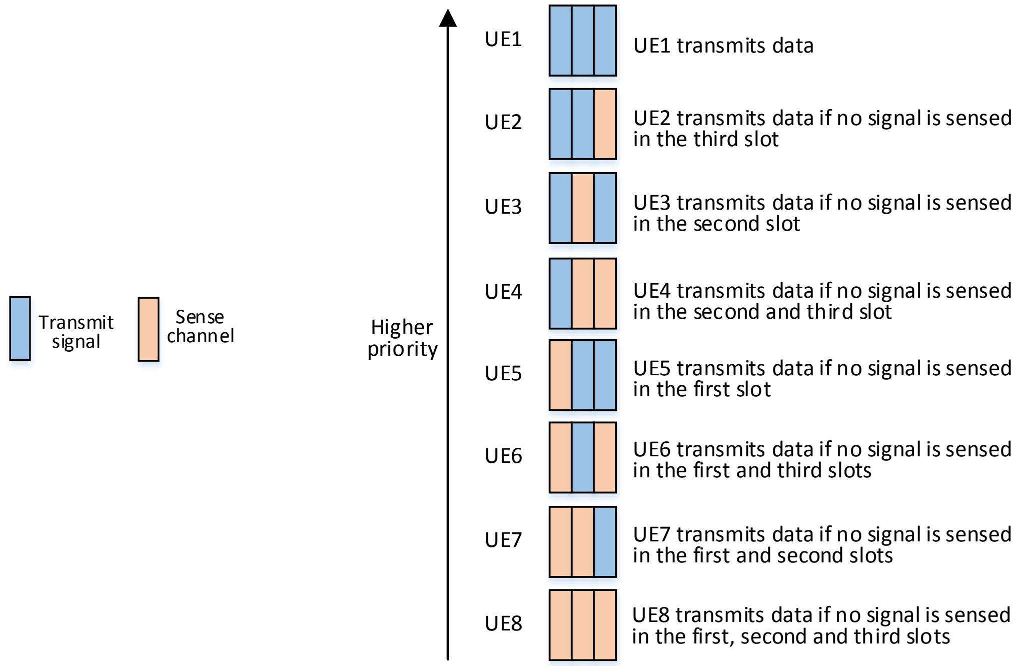


Figure 36. Transmission of announcement signals and channel sensing based on pre-established priorities.

4.2.1 Announcement slots

The proposed grant-free scheduling scheme is based on the transmission of AN signals on some dedicated slots referred to as AN slots. The AN signals do not include useful information or data that should be decoded by other UEs. The aim of transmitting these signals is that other UEs sense the channel as busy, and then interpret that a higher priority UE will use the channel. In this case, UEs with lower priorities will decline to transmit in the next radio resource to avoid collisions. The use of short TTIs to send these AN signals will increase the radio resource efficiency.

In legacy LTE, a TTI is composed of 14 orthogonal frequency-division multiplexing (OFDM) symbols spanning a 1 ms duration. Considering that latency is in general a function of the TTI duration, shorter TTI formats are being proposed in Rel.15 and Rel.16 3GPP standards for latency reduction [49]. The 5G Radio Access will be composed of an LTE Evolution, and a New Radio Access Technology (NR). The LTE Evolution Radio Access will work on the existing traditionally used sub-6GHz spectrum and will support legacy devices hence ensuring backward compatibility. On the other hand, NR will not be constrained by backward compatibility and will operate on new spectrum. In this context, different shortened TTI solutions are being proposed/studied by the 3GPP for each 5G radio access technology based on the backward compatibility constraints.

- For LTE Evolution Radio Access, UEs supporting latency reduction shall be able to coexist with legacy UEs in the same serving cell. This requirement would restrict potential new TTI formats. In this context, short TTI lengths based on 2, 3 and 7 OFDM symbols are being considered (short TTI of 7 OFDM symbols are also referred to as 1-slot TTI) as presented in [50].
- In NR, backward compatibility is not required. In this case, short TTI formats with smaller number of OFDM symbols (e.g. 1 or 2) are being considered. In this case, new control/data channels, reference signals, and related UE behaviors need to be defined. In addition, various TTI lengths should flexibly be applicable depending on the service type of each UE, and UEs with various TTI lengths shall be able to coexist in the same carrier efficiently [48]. Another approach considered for NR is to use higher subcarrier spacing to shorten the OFDM symbol duration of a TTI.

An important aspect of this scheduling scheme is to determine the number of AN slots to be used to manage the access to the shared resources of UEs. This decision has to be based on the following main factors:

1. Number of UEs sharing the same radio resources. For example, if we want to guarantee a collision free scheduling method, *n* AN slots are necessary to manage the access of from $2^{n-1}+1$ to 2^n UEs.
2. The specific communication requirements in terms of reliability and latency/determinism of the industrial application or service supported. Applications and services establish the maximum tolerable latency and the maximum probability error. Based on this data, the collision free condition can be relaxed while still guaranteeing the communication requirements of the specific application or service. In this context, more than 2^n UEs could be managed with *n* AN slots while still guaranteeing its communication requirements.
3. The traffic arrival time for the UEs sharing the radio resources. If a non-collision free scheduling scheme is finally designed, the traffic arrival time of UEs sharing radio resources should also be considered since it will also determine the probability of collision and then the probability of error.
4. Ensuring radio resource efficiency. We need to ensure that the amount of radio resources needed to carry out the proposed scheduling process (AN slots resources and shared data resources) is lower than the amount of resources that should be necessary to guarantee the communication requirements of the supported applications and services without any contention resolution mechanism. Splitting a given number of UEs in two different groups might result more efficient in terms of the use of radio resources than trying to satisfy its stringent communication requirements when all UEs share the same radio resources.

4.2.2 UEs sharing radio resources

By sensing the AN signals of higher priority UEs, collisions can be avoided with the proposed grant-free scheduling scheme. In this context, a key important aspect is to guarantee that UE sharing the same radio resources can sense the AN signals of each other. To this end, we propose to exploit the presence of the eNB to establish the group of UEs that share the same resources. The eNB can make use of information about the position of each node in the cell or other available information to ensure that UEs in the same group can listen one another.

As mentioned in previous section, the number of UEs in the same group should be established to guarantee deterministic communication (guarantee the communication requirements of the applications and services supported in the cell) while increasing the resource utilization efficiency. In this context, the specific communication requirements of UEs and the traffic arrival time for the different UEs should also be considered.

4.2.3 UEs priorities and channel access probability

As otherwise specified, it is important to guarantee the same channel access probability to all UEs. In this context, priorities should change dynamically to guarantee the same opportunities to all UEs. This is one of the aspects that need to be further investigated. In this context, we are considering different alternatives from a totally distributed priority management scheme or also exploiting the presence of the eNB in the cell.

4.3 Performance Evaluation

During the following months, we will evaluate analytically and through system level simulations the proposed scheduling scheme. We have identified four main reference schemes:

1. The SPS scheme defined in the 3GPP standards.
2. The proposal presented in [45]. This work proposes that UEs transmit on dedicated resources and retransmissions will be carried out on shared resources.
3. A grant-free scheduling that proposed to use shared resources without contention resolution. In this case, the number of UE per group is established to satisfy communication requirements in terms of latency and reliability.
4. The grant-free scheduling presented in [47] that proposes to send several repetitions of the same packet to increase the successful reception rate.

The ability to satisfy the communication requirements in terms of reliability and latency/determinism of each scheme will be evaluated. As previously mentioned, another important aspect will be to evaluate the radio resource utilization efficiency achieved with the different schemes.

5 Conclusion

D2.3a describes the work carried out during the first half of the Project (M7-M18) in task T2.3 to define new solutions for low latency and high reliability deterministic industrial wireless networks capable to support more flexible and reconfigurable CPPS under the paradigm of Industry 4.0. Different studies have been carried out within T2.3, some based on simulation while other on experimental trials:

1. We have designed a load-balancing scheme for scalable & self-organizing industrial wireless networks. The proposed load-balancing scheme is able to detect changes in the industrial environment and adapt the configuration of communication links ensuring end-to-end connectivity and high reliability levels in the network. We are currently finalizing a research paper to be submitted to the Computers in Industry Journal:

   M. Carmen Lucas-Estañ, Javier Gozálvez, "*Load Balancing for Reliable Self-Organizing Industrial Wireless Networks*", in preparation to be submitted to *Computers in Industry*.
2. We have developed a prototype for reliable industrial wireless communication. This prototype exploits diversity and redundancy to guarantee a reliable and low-latency communication to support mobile industrial applications. The developed prototype has been integrated and evaluated in the Tekniker neutral experimentation infrastructure. This work has resulted in two research papers. The first paper has been accepted to participate in the 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) that will take place in Torino, Italy between 4th-7th September 2018 (http://ieee-etfa2018.com/id.php):

   M.C. Lucas-Estañ, J.L. Maestre, B. Coll-Perales, J. Gozalvez, I. Lluvia, "An Experimental Evaluation of Redundancy in Industrial Wireless Communications", submitted to the conference the *23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*.

   A second research paper is under preparation to be submitted to a relevant journal in the field of industrial communications.
3. We are studying a novel scheduling solution for deterministic 5G industrial communications. The proposed scheduling scheme aims to ensure the

deterministic latency levels of industrial wireless communications under the paradigm of Industry 4.0. This study is currently under development.

Next steps within task T2.3 include the evaluation and tuning of the proposed 5G-based scheduling scheme analytically and by simulation. In addition, we are currently working on a new study to guarantee flexible and high reliable industrial wireless networks. The proposed reference communication and networking architecture defined in T2.1 consider the use of RAN slicing to support different services with different communication requirements. In this context, a challenging task will be to manage the radio resource assigned to each slice in order to ensure that the requirements of the industrial applications and services supported by each slice are satisfied. In addition, isolation among slices must be guaranteed to avoid negative interactions.

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