IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 3, 2019, accepted June 19, 2019, date of publication July 8, 2019, date of current version August 2, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2927298

Analysis and Evaluation of a Wired/Wireless Hybrid Architecture for Distributed Control Systems With Mobility Requirements

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This work was supported in part by the Basque Government, Spain, under Grant U4INDUSTRY (ELKARTEK).

ABSTRACT Wireless communications offer significant benefits over wired communications, which has increased their popularity in industrial applications. Nevertheless, the existing wireless standard technologies do not satisfy the requirements demanded by the most critical industrial applications and thus, wired communications cannot be directly replaced by wireless solutions. Moreover, the inclusion of movable nodes in the network brings new challenges, such as the handover mechanism. In this paper, a hybrid wired/wireless architecture designed for industrial control applications is proposed. To control the wired network, a time-sensitive network (TSN) is used and to control the wireless network a medium access control (MAC) protocol is designed. In order to communicate both networks, a bridge that acts as a deterministic access point (AP) with real-time features is also proposed. One of the fundamental parts of the proposed architecture is that it can be used in applications with mobility requirements. Hence, a soft-handover algorithm is designed which guarantees uninterrupted communication during its execution without the need for a second radio interface and with reduced growth in network overhead. The proposed architecture is evaluated in order to assess its performance. This paper extends our previous work, including both a theoretical analysis to determine the delay bounds of the proposed architecture and a comparison between the performances of the proposed handover algorithm with other algorithms proposed in the literature. The evaluation has been carried out through OMNeT++ simulations. The results demonstrate the superiority of the proposed handover algorithm compared with other state-of-the-art solutions.

INDEX TERMS Handover, IEEE 802.11, industrial communications, industrial wireless sensor and actuator networks, real-time communications, SHARP, TSN, wireless communications.

I. INTRODUCTION

Wireless technologies have been bringing new opportunities and challenges for industrial automation. That is why in recent years, the use of Industrial Wireless Sensor and Actuator Networks (IWSAN) has emerged as a suitable solution for applications in industrial environments [1], [2]. IWSAN-based solutions provide significant cuts in the costs derived from the deployment and maintenance, more flexibility concerning physical distribution and offer an easy deployment with movable objects [3].

Several wireless standards such as ISA 100.11, WIA-PA, ZigBee, WirelessHART and WISA have been proposed to be used in industrial applications. Both ISA 100.11a and WIA-PA have been designed for industrial applications with relaxed requirements on latency and real-time (RT) such as monitoring [4], [5]. In the case of ZigBee, a deterministic communication can be guaranteed in beacon-enabled mode but only for a few number of nodes [4]. WirelessHART guarantees highly reliable communications but it does not deal with packet losses due to link bursts [6]. WISA has been designed for industrial applications with stringent requirements [7] and it can offer less than 20 ms end-to-end latency [8]. All these standards are based on the physical layer of IEEE 802.15 family whose data rate is limited and offers low scalability within a specific cycle time [9]. Thus, recently, there is an increasing interest in the use of IEEE 802.11 physical layer in industrial applications,

The associate editor coordinating the review of this manuscript and approving it for publication was Faisal Tariq.

since it offers higher throughput than previously mentioned low-energy and low-throughput IEEE 802.15-based industrial wireless communication standards [9]. This feature is interesting for applications such as closed-loop control, in which a reduced latency is favored over energy efficiency. For example, WIA-FA is the first wireless technology specification developed for high-speed, industrial control applications. This technology defines a MAC layer based on multiple access mechanisms such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and data aggregation. The guaranteed cycle time is in the order of several milliseconds considering several tens of nodes, which makes this technology suitable for some industrial applications but not for the most critical ones.

The industrial Wireless Local Area Network (iWLAN) technology, is also based on IEEE 802.11. In order to ensure a deterministic communication, the Point Coordination Function (PCF) used in the MAC layer of IEEE 802.11 standard is redefined as industrial PCF (iPCF). Although iPCF provides coordinated medium access, it requires a polling mechanism that increases the overhead of the communication affecting the latency of the system. Therefore, the search for a wireless communication protocol that guarantees the strict requirements of the most critical industrial applications is still a growing research field as of today.

Moreover, until now, since the most critical industrial applications have been using wired centralized networks, mobility has been rarely required. However, with the Industry 4.0 revolution, mobility is becoming a requirement of industrial applications [10]. The inclusion of movable wireless nodes in wired networks is often complex or even impossible [5]. In these cases, the solution lies in the implementation of a heterogeneous network composed of both a wired and a wireless network [11]–[13]. In these cases, wireless communications can be seen as an extension to existing wired networks. In order to correctly manage the changes in the topology due to the movement of the wireless devices, a handover algorithm is also needed [14].

In this paper, a hybrid wired/wireless centralized architecture designed for industrial applications with strict requirements in terms of robustness, determinism and RT is proposed, besides from expanding the wired network used in those applications to a wireless domain. Time-Sensitive Networking (TSN) technology has been selected to control the wired segment of the proposed hybrid architecture. TSN technology has been chosen in contrast to other proprietary solutions such as EtherCAT. Moreover, in order to control the wireless network, a wireless MAC scheme with deterministic and RT features is proposed. This MAC scheme is based on the IEEE 802.11 physical layer. The proposed hybrid architecture ensures a seamless communication between both media through an access point (AP) designed specifically for this architecture. In order to incorporate mobile devices to the proposed hybrid architecture, a soft-handover algorithm is designed which guarantees an uninterrupted communication during its execution without the need for a second radio interface and with a reduced growth in network overhead. This mechanism allows to expand the application area and to obtain even more benefits from using wireless communications. This paper extends the description and improves the soft-handover algorithm presented in our previous work [15]. Moreover, the previous work is extended through an exhaustive analysis of the whole hybrid architecture. The integration of a TSN network with the proposed wireless MAC is presented for the first time in this paper as well as the provided theoretical analysis and the comparison between the proposed soft-handover algorithm with other state-of-the-art handover algorithms.

The rest of the paper is structured as follows: background research and an analysis of the related work are presented in Section II. In Section III, both the proposed hybrid architecture and the proposed soft-handover algorithm are described. In Section IV a theoretical analysis to determine the delay bounds of the proposed hybrid architecture is presented. The simulation setup and the obtained results are described in Section V. Finally, in Section VI, conclusions are discussed.

II. BACKGROUND AND RELATED WORK

A. INDUSTRIAL COMMUNICATIONS

Industrial applications can be divided into different categories depending on their functional and service requirements. Here we can distinguish between [16]:

- Condition Monitoring (CM)
- Process Automation (PA)
- Factory Automation (FA)

CM applications collect data provided from different types of sensors distributed over the whole manufacture area. They are responsible for monitoring signals such as temperatures, vibrations, etc. The collected information is usually not sensitive to packet losses and their RT and latency requirements are quite relaxed.

The applications in PA are related to monitoring and diagnosis of processes and elements. The manufacture of chemical, oil or gas products, heating, cooling or pumping procedures and machinery monitoring are typical PA applications. These applications are characterized by having relatively slow and continuous processes, in which large amounts of data are exchanged. Their RT and latency requirements are stricter than those of CM applications, but they are still relaxed.

Finally, FA applications are typically characterized by RT control systems that perform discrete actions such as assembly lines and they involve motion control. The applications belonging to FA have strict requirements in terms of RT and reliability due to the precise operations they perform [17].

In contrast, not all industrial communication systems are equal in terms of RT requirements or criticality of the data to be transmitted. Hence, in order to classify industrial applications based on their RT capabilities, the maximum delay bound of a successful transmission, the communication protocol delivery time (i.e. the latency) and the jitter must

TABLE 1. Industrial application requirements.

Requirements	Industrial application		
	CM	PA	FA
RT requirements	Non-RT/ Soft RT	Soft RT	Hard RT/ Isochronous RT
Latency	≥ 100 ms	10 – 100 ms	< 10 ms
Jitter	-		≤ 1 ms
Reliability (PLR)	10^{-3} – 10^{-4}		10^{-6} – 10^{-12}
Cycle time	100 ms – 10 s	1 ms – 5 s	50 μs – 1 ms
Coverage area	100 m – 500 m		10 m – 100 m
Mobility	≤ 5 km/h		≤ 30 km/h
Number of devices	100 – 1000	100 – 300	10 – 100
Data size	30 bytes – 1500 bytes		15 bytes – 64 bytes

be considered. The jitter is defined as the maximum deviation of consecutive cyclic data transmission.

Hence, the classification must be done according to [16]:

- Non-RT applications
- Soft RT applications
- Hard RT applications
- Isochronous RT applications

While non-RT applications, such as those in charge of monitoring, have no requirement regarding deadlines, the other three application categories have some deadline requirements. Although soft RT applications have requirements regarding deadlines of the data delivery, they are relaxed, and the performance of the system is not compromised in case a deadline is missing. In contrast, both hard RT and isochronous RT applications must meet strict deadlines to avoid causing an error in the application or human injuries. Note that isochronous RT applications have more restricted requirements in terms of jitter and latency than hard RT applications.

In addition to the RT requirements, other parameters such as the network reliability (expressed through Packet Loss Rate (PLR) metric), the cycle time of the applications or the length of the data packets to send must also be considered. Hence, the reference requirements of CM, PA and FA applications are shown in Table 1 [8], [16], [18], [19].

The research work presented in this paper is focused on FA applications. Specifically, we are focused on industrial control applications in which it is necessary to meet strict requirements in terms of time and reliability, such as, Networked Control Systems (NCS) or Distributed Control Systems (DCS) [20].

B. COMMUNICATIONS FOR INDUSTRIAL APPLICATIONS

Traditionally, sensors and actuators have been using field buses, whose main advantages are that they can be integrated into complex systems, in addition to the reliability and the data rate that they offer. Yet, these communications are currently being replaced by variants of the IEEE 802.3 standard under the alternatives called Real-Time Ethernet (RTE). It is noteworthy that, if the technological aspects used by the original IEEE 802.3 standard are analyzed in detail, such as its random medium access mechanism, it can be seen that it does not meet the requirements of the FA applications. Consequently, a set of standards called TSN are being defined to provide deterministic communications with RT performance over Ethernet.

The next logical step in the evolution of communication at the field level is the inclusion of wireless networks. Therefore, over the years and with the Industry 4.0 revolution, the inclusion of wireless communications with RT requirements has been gaining popularity in industrial applications. Since IEEE 802.11 was conceived as an extension of the IEEE 802.3, the ability to exchange packets coherently between both standards allows a high degree of integration. Nevertheless, its contention-based MAC protocol does not guarantee a deterministic behavior and thus, it is not suitable for FA applications [21]. Moreover, the RT performance and high reliability are the key factors of those applications rather than the throughput, and IEEE 802.11 standard lacks these requirements. Hence, a natural evolution of IEEE 802.11 may be the addition of Time-Sensitive capabilities in the same way that Ethernet has evolved into TSN. Currently, work is being done to introduce Time-Sensitive capabilities to IEEE 802.11. One of the proposed solutions is through an architecture named Synchronous and Hybrid Architecture for Real-time Performance (SHARP) [22] which is designed for the most critical industrial applications.

With the aim of providing to IEEE 802.11 RT guarantees along with a deterministic behavior, several TDMA-based MAC protocols have been proposed in the literature [23]–[26]. Using TDMA, in addition to guaranteeing an upper bound of the delay, packet collisions rarely happen even in high-density networks due to a well-organized scheduler [27]. However, the proposed MAC protocols in the literature cannot manage a high number of nodes while fulfilling the requirements of FA applications. Within the SHARP architecture [22], a TDMA-based wireless MAC protocol is defined which offers a high packet rate, high reliability and it is able to guarantee the 1 ms control cycle required by most critical industrial applications. However, this architecture does not currently support mobile wireless devices.

C. HANDOVER ALGORITHMS

A fundamental requirement to consider when designing a handover mechanism is the interruption of the communication during its execution. There are two ways to carry out a handover: hard-handover and soft-handover. With the former, the communication between the associated AP and the node that is requiring a handover is interrupted leading to packet losses. In contrast, the soft-handover algorithms can keep the communication uninterrupted during the whole handover process to avoid packet losses during its execution. Hence, the most critical industrial applications require the use of soft-handover algorithms, where the interruption of the communication is avoided, maintaining the connection between both APs during the execution of the handover. Note that the soft-handover algorithms achieve an uninterrupted communication through more complex algorithms and using more network resources, which entails an increased network overhead. Moreover, soft-handover algorithms often require even a second radio interface, which leads to an increase in the cost and complexity of the system.

1) IEEE 802.11 STANDARD-BASED HANDOVER ALGORITHMS

The legacy handover process included in the IEEE 802.11 standard is a hard-handover mechanism in which the communication can be interrupted up to a few seconds [28]. Even though the IEEE 802.11r amendment includes mechanisms to speed up the conventional authentication phase, it is shown in [29], [30] that the interruption in the communication is still between 13 ms and 30 ms during the handover. Moreover, the analysis made in [30] is only valid when a re-association occurs. In [31], a handover mechanism is proposed in which the wireless nodes make a handover believing that they are only changing the radio channel. Nevertheless, the communication is interrupted during 130 ms. Moreover, the main drawback of this proposal is that it needs two IEEE 802.11 interfaces. In contrast, there are several proposals in the literature focused on enhancing the scanning phase to reduce its duration while keeping the other phases of the IEEE 802.11 handover process unchanged. The proposal in [28], optimizes the scanning phase through IEEE 802.11k amendment collecting information related to the wireless medium before executing the handover. By means of this mechanism, it is only necessary to scan the relevant channels. Another solution is to propose a multi-beacon scheme to eliminate the scanning phase as done in [32], [33]. In the communication scheme proposed in [32], a beacon period is defined in which each AP transmits beacon packets using the channels of its neighboring APs. In this way, the mobile nodes will receive during this period the beacons sent by all available APs in their coverage area and decide to execute a handover or not. In contrast, in [33], these beacons are not sent during a dedicated period and a second IEEE 802.11 interface is used for that purpose. It is necessary to emphasize that none of the mentioned proposals prevents the interruption of the communication during the handover process.

In the same way, there are other handover algorithms that focus on the position of the node to reduce (but not avoid) the time interval in which communication is interrupted due to a handover [34], [35]. Finally, a mechanism to avoid this interruption is proposed in [36], but it is at the expense of exploiting a predictable geometry, such as the motion paths of trains. Note that all these solutions besides being evaluated under a network with a reduced number of nodes, they have been assessed through non-deterministic communication protocols that are not suitable for FA applications.

2) LTE HANDOVER ALGORITHM

Current cellular technologies, such as LTE and the upcoming Fifth Generation (5G) systems are considered as solutions to be used in industrial applications since they can satisfy low-latency communication [7], [37], [38]. Given that cellular networks are dynamic and flexible communication networks able to adapt their configuration to changes in the environment, the handover algorithm used by LTE is analyzed in order to determine if it could be used in the most critical industrial applications.

As in IEEE 802.11 standard, the handover algorithm used in the current LTE technology causes an interruption in the communication [39]. Ideally, in LTE, the communication is interrupted during the time interval needed to carry out the handover process. In practice, the existing processing times and propagation delays can increase the interruption of the communication. The International Telecommunication Union (ITU) establishes a typical LTE handover execution time of 27.5 ms - 60 ms [40] whereas the 3rd Generation Partnership Project (3GPP) establishes it in 49.5 ms [41]. In [42], the interruption caused due to an LTE handover is evaluated in a real scenario. The measurements show an interruption of 40 ms during the handover. In [43], a handover skipping algorithm is proposed. The aim of this algorithm is to determine if an AP must be omitted when selecting an AP to execute a handover. The proposed solution combines the measured Reference Signal Received Power (RSRP) and its rate of change to determine the target AP. Despite this mechanism, the LTE handover algorithm is not suitable for FA applications due to the interruption in the communication during its execution.

III. PROPOSED HYBRID ARCHITECTURE AND ANALYSED SOFT-HANDOVER ALGORITHM

A hybrid centralized architecture, designed for scenarios with strict requirements in terms of robustness, determinism and RT is presented in this section. The required performance is obtained with a TSN/IEEE 802.11 RT MAC scheme. Moreover, this architecture is combined with the proposed soft-handover to incorporate mobile wireless nodes. The analyzed handover mechanism focuses on maintaining the communication between the AP and the node during the whole handover process, without the need for a second radio interface like other proposals in the literature and with a reduced growth in network overhead.

A. NETWORK TOPOLOGY

The considered network architecture comprises a controller (a PLC), a TSN network, several APs connected to the TSN network to cover the wireless area, and sensors and actuators distributed along the hybrid network (named nodes throughout the paper). The considered architecture is shown in Fig. 1. The PLC will be placed in the wired segment to avoid compromising the process due to the shared medium of the wireless network. Moreover, to guarantee the requirements needed by the control applications, the proposed hybrid architecture will follow a tree topology, which offers both high performance and high scalability. If we focus on the wireless segment, a star topology is proposed. In the FA applications, where the control cycle period is low and a reduced latency is

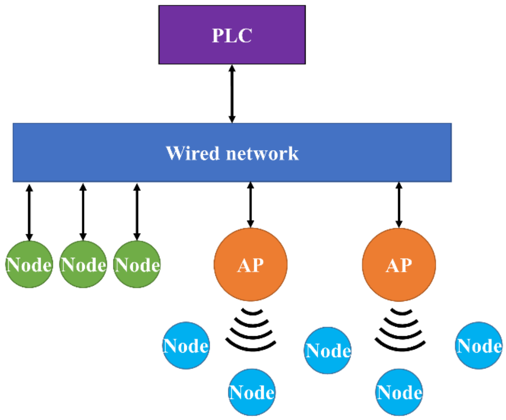

FIGURE 1. Proposed hybrid network topology.

sought, a star topology is more suitable because the wireless coordinator (the AP in this case) schedules RT packets in a more restrictive way [3], [44].

B. PROPOSED HYBRID TSN/IEEE 802.11 MAC SCHEME

In order to provide a reliable and deterministic communication, a hybrid RT TSN/IEEE 802.11 MAC scheme is proposed.

1) PROPOSED IEEE 802.11 MAC PROTOCOL

To control the shared wireless medium, an improved version of the TDMA-based MAC scheme defined in [45] is considered. This MAC protocol is defined in order to guarantee a deterministic and RT communication over wireless medium. In this paper, the definition of the proposed wireless MAC is improved, as will be detailed further. The proposed MAC protocol is combined with the IEEE 802.11 physical layer due to the increasing interest in the use of this standard in industrial applications in contrast to the low-energy and low-throughput IEEE 802.15-based industrial wireless communication standards [3]. The proposed wireless superframe, which is shown in Fig. 2, is divided into two communication periods: one dedicated mainly to transmitting/receiving RT data packets based on a defined TDMA scheme and another one dedicated to transmitting best-effort (BE) information using the contention-based legacy IEEE 802.11 MAC.

a: REAL-TIME (RT) PERIOD

The RT period is based on a dynamic scheduler that will be modified only when a node is associated/dissociated with the AP. The AP is responsible for calculating and distributing the scheduler that the nodes will follow under its coverage area. This scheduler includes the transmissions instants of every RT data packets and acknowledgments (ACKs). While a node is associated with the AP, the slots assigned to it will be non-transferable and cannot be shared with other nodes. As shown in Fig. 2, the RT period divides the superframe into multiple slots which are described below. Note that there is a Short Interframe Space (SIFS) interval between the slots to

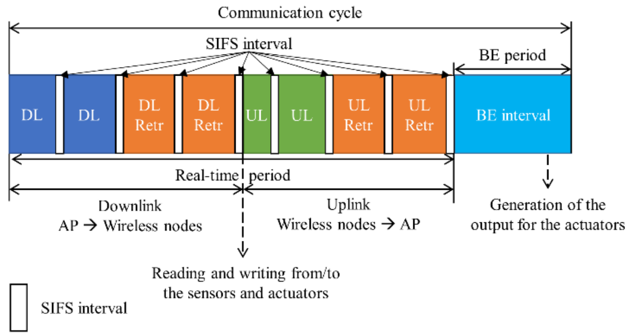

FIGURE 2. Proposed wireless MAC superframe structure.

guarantee that the periodic RT traffic has a higher priority against the BE traffic.

DOWNLINK (DL) SLOTS

Periodic RT data packets transmitted from the AP to the nodes are transmitted during these slots. Each node associated to an AP will have a DL slot assigned to receive, through the AP, the periodic RT traffic sent by the PLC.

As shown in Fig. 2, when the DL retransmission slots end, the value of the actuators (both wired and wireless) must be updated and the new states of the sensors (both wired and wireless) must be read. Thus, in order to synchronize with the reception of the periodic RT traffic sent by the PLC, the DL phase must be scheduled before the uplink (UL) phase as shown in Fig. 2.

In order to increase the reliability of the wireless communication, once the AP transmits the DL packet, the node must respond with an ACK if the reception of the RT packet is correct, and with a negative acknowledgment (NACK) if they do not receive the expected DL packet or if the reception is incorrect. Whether the AP receives a NACK or does not receive any response from the node to which the packet was addressed, the DL packet will be saved in a queue for its retransmission in the following DL retransmission slots.

DOWNLINK RETRANSMISSION (DLRetr) SLOTS

The main task of these slots is to retransmit the periodic RT data packets of the DL period. All transmissions made in these slots must be acknowledged and the AP will retransmit the packets based on the retransmission queue. The first packet in the queue will be the first to be retransmitted.

Finally, if the DLRetr slots are left unused, they can be employed for other purposes such as to transmit BE traffic or to send changes in the scheduler due to a handover.

UPLINK (UL) SLOTS

Periodic RT data packets are transmitted from the nodes to the AP during these slots. Each node associated with an AP will have assigned a UL slot to transmit periodic RT traffic to the PLC.

As shown in Fig. 2, before transmitting UL data packets, the value of the actuators (both wired and wireless) must be updated and the new states of the sensors (both wired and wireless) must be read.

Unlike in DL slots, only the last UL slot must be acknowledged. Therefore, the duration of the UL slots (except the last one which has the same duration as the DL slots) is shorter than DL slots. Despite the lack of acknowledge packets, the AP will keep track of the packets it has received on these UL slots. The AP will use the information of the scheduler to know which nodes have sent the successfully received UL data packets. This information will be broadcasted by the AP to all wireless nodes in the network as a response to the RT data packets sent by a node during the last UL slot.

If the wireless nodes receive this response packet, they will check if the AP has received the UL RT data packet sent by each of them. If the transmitted UL RT data packet has not been received correctly, the node will save the previously sent UL packet in a queue for its retransmission in the following UL retransmission slots. In the same way, if a node does not receive the broadcasted response packet, it will also save the UL RT data packet for its retransmission just in case.

UPLINK RETRANSMISSION (ULRetr) SLOTS

The main task of these slots is to retransmit the periodic RT data packets of the UL period. All transmissions made in these slots must be acknowledged. Moreover, the retransmissions must be done in an orderly fashion in order to prevent several nodes from retransmitting at the same time. In order to do so, priorities are established. These priorities will be assigned by the AP when defining the scheduler. Note that a node that has been newly associated with an AP will be assigned a priority that is not being used by any neighboring node associated with this AP. Thus, if a wireless node has a UL RT data packet to retransmit, it will wait for a short period (t_{ret}) defined based on its priority as stated in (1). This time interval will correspond to the maximum propagation delay (t_{prop}) of the network. The node with the greatest priority ($p = 0$) will have the right to retransmit immediately without having to wait.

$$t_{ret} = p \cdot t_{prop}. \tag{1}$$

If the channel remains idle after this time interval, it means that no wireless node with higher priority has tried to retransmit and, hence, UL retransmission is possible. Once the UL retransmission slot ends, the node that has retransmitted a packet will have the lowest priority and the others will increment their priority by one.

Finally, if the ULRetr slots are left unused in a control cycle, they can be used to transmit BE traffic or changes in the scheduler due to a handover. In the latter case, the device should wait for a predefined time interval greater than the maximum t_{ret}, i.e. the maximum time interval that a wireless node that wants to retransmit periodic UL traffic can wait. In this way, the transmission of the scheduler changes is prevented from colliding with periodic RT traffic retransmission from another node.

b: BE PERIOD

This period is used to transmit the BE packets using the contention-based legacy IEEE 802.11 MAC. Note that the AP must access the medium some microseconds before the BE period ends in order to ensure that no other node begins to transmit a BE packet prolonging the contention period i.e. BE interval. This method, proposed in [25], prevents any BE packet from invading the RT period.

c: DURATION OF THE SLOTS OF THE REAL-TIME PERIOD

The DL (t_{DL}), DL Retr (t_{DLRetr}), UL Retr (t_{ULRetr}) and the last UL (t_{lastUL}) slots will have the same duration, which is equivalent to:

$$t_{DL} = t_{DLRetr} = t_{ULRetr} = t_{lastUL} = t_{data} + t_{ACK} + t_{prop}, \tag{2}$$

where t_{data} and t_{ACK} define the duration of an RT data packet and an ACK/NACK packet, respectively, which is defined as follows:

$$t_{data}\ or\ t_{ACK} = t_{preamb} + t_{signal} + \left\lceil \frac{N_B + N_{SB} + N_{PB}}{N_{DBPS}} \right\rceil \cdot t_{OFDM_{Symb}}, \tag{3}$$

where t_{preamb}, t_{signal} and $t_{OFDM_{Symb}}$ are the duration of the preamble, the signal symbol and the Orthogonal Frequency Division Multiplexing (OFDM) symbol, respectively. Moreover, N_B is the number of bits in the payload, N_{SB} defines the 16 bits added before the payload, N_{PB} indicates the 6 bits added after the payload and N_{DBPS} is the number of bits in an OFDM symbol. Finally, $\lceil \cdot \rceil$ is the operator ceil, which rounds up the value.

In contrast, the UL ($t_{notLastUL}$) slots (except the last one) will have a duration equivalent to:

$$t_{notLastUL} = t_{data} + t_{prop}. \tag{4}$$

d: DYNAMIC SCHEDULER

The proposed MAC scheme must be combined with a dynamic scheduler to cope with the changes in the network. Considering that the control cycle of the system remains invariant, as well as the duration of the defined wireless superframe, the number of UL and DL slots will vary depending on the number of the associated nodes in each AP.

On the one hand, the duration of the DL interval (DL + DLRetr slots) must be fixed regardless of the number of associated nodes because all the nodes (wired and wireless) update the actuators' values and read the new status of the sensors before transmitting the new UL data packets. In case of allowing the DL interval to last longer than this point, we would reduce the time interval used to transmit UL data traffic as well as increase the value of the minimum MAC to MAC delay possible. It is also necessary that the duration of the DL interval be fixed in order to synchronize the transmission and reception of the packets coming from the wired network. The unused DL slots will be used for retransmissions. Note that a minimum of slots dedicated to DL retransmissions must always be guaranteed.

On the other hand, the duration of the UL interval (UL slots + ULRetr slots), is variable. Since a minimum BE interval must be guaranteed within a wireless superframe, the rest of the superframe duration can be used for the UL transmission, again guaranteeing a minimum of slots dedicated to UL retransmissions. If there is more time available but is not enough for a new UL retransmission slot, this time interval is going to be added to the BE interval.

e: IEEE 802.11 MAC-LEVEL HEADER

Along with the proposed MAC scheme, it is also necessary to customize the MAC-level headers of the RT data packets in order to obtain a reduced control cycle. The MAC header of the IEEE 802.11 standard is too large for the considered application since the shortest IEEE 802.11 data packet MAC header is 24 bytes long as shown in Fig. 3 [46].

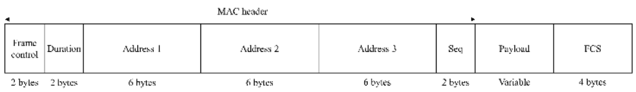

FIGURE 3. Minimum IEEE 802.11 data packet MAC-level header.

A new compressed MAC header, which is shown in Fig. 4, is proposed to be used in RT data packets. The IEEE 802.11 MAC headers of the RT data packets have been modified and shortened with two objectives: Firstly, to reduce the inefficiencies related to the packet overhead—considering the reduced amount of information that is sent in the industrial communications [7]—, and secondly, to include the request and resolution signals of the handover.

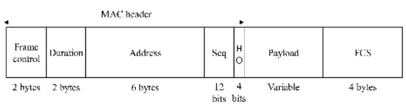

FIGURE 4. Proposed MAC header of the RT data packets.

The first three fields (frame control, duration and address 1) and the last field, Frame Check Sequence (FCS), of the standard IEEE 802.11 data frame MAC header shown in Fig. 3, constitute the minimal packet format of the IEEE 802.11 standard. Hence, they have been kept in our proposal as shown in Fig. 4. In addition, the sequence field, which is part of the standard data packet header and is formed by 16 bits, has been included as well. In this MAC-level header proposal, the RT data packet is identified by the first 12 bits of the sequence field and the rest 4 bits, redefined as HO, will be used to indicate the state of the handover process.

Given that the HO field is used to make all the notifications of the handover process, it is not necessary to send additional packets. In addition to be predictable, this allows not to increase the wireless traffic during a handover. Thus, each time a node wants to start with the handover process it will only have to indicate it in the HO field of the MAC-level header of the periodic RT data packet exchanged with the AP (which it will then send to the PLC). In this way, the time required to execute the handover process is reduced and the network overhead due to a handover is not increased.

2) INTEGRATION OF TSN AND THE PROPOSED WIRELESS MAC SCHEME

Among the existing wired RTE protocols able to fulfill the strict requirements of FA applications, TSN technology has been selected to control the wired segment of the proposed hybrid architecture. TSN technology has been chosen in contrast to other proprietary solutions such as EtherCAT. Moreover, TSN replaces the proprietary RTE solution proposed in [45]. TSN is a set of IEEE 802 sub-standards that aims to provide deterministic communication with RT guarantees over Ethernet by using time synchronization and scheduling information which is shared between all the devices of the network through TSN switches.

The expected use of TSN in future automation systems and the similarities of TSN's traffic scheduler with the proposed wireless MAC scheme allows a high degree of integration between both schemes. Moreover, some of the concepts considered by TSN can be brought to wireless networks [47], so that the wireless segment could be seen as an extension of TSN.

The core of TSN is the IEEE 802.1Qbv [48] sub-standard which is responsible for scheduling the traffic in a deterministic way using the principle of time-triggered communication. To do so, TSN defines time windows, in which the transmission of the most critical packets is foreseen without being interfered by other less critical transmissions. These time windows must be defined in a scheduler. Moreover, each Ethernet packet will be assigned to a queue based on its priority. Hence, during the defined time windows, queues that are not transmitting will be blocked to ensure that non-scheduled traffic is transmitted. In order to block the queues, the concept of transmission gates is introduced, which are used to enable separate transmission queues, being their states open and closed. The state of the gates is defined within a schedule and the TSN switches will be in charge of controlling that the gates are opened at the scheduled time in order to guarantee the low latencies required in the network.

Hence, the mechanism of IEEE 802.1Qbv controls the access to the wired medium within the proposed hybrid architecture. The defined time windows used to transmit the RT packets must be scheduled in such a way that it can achieve a perfect synchronization with the previously described wireless MAC scheme. The synchronization between both MAC schemes is shown in Fig. 5.

In order to achieve the mentioned synchronization, the scheduled time window dedicated to transmitting RT data packets between the PLC and the AP must be defined before the beginning of the DL slots of the wireless superframe. The reason for this is that the AP needs to have received the RT data packets from the PLC before sending them to the wireless medium. In the same way, the AP needs to have received the RT data packets sent from the wireless

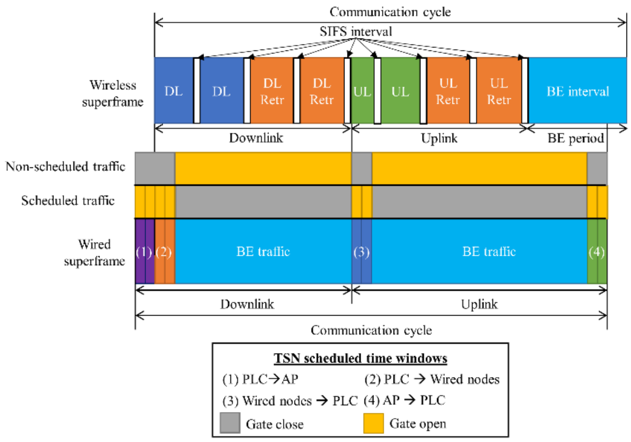

FIGURE 5. Integration of the proposed wireless MAC and TSN.

medium before sending them to the PLC. That is why the scheduled time window dedicated to transmitting the RT data packets between the AP and the PLC must be defined after the ending of the UL slots of the wireless superframe. The remaining time interval left by the scheduled time window, within the wired superframe, will be used for the transmission of BE traffic and to send changes in the scheduler due to a handover. These packets will have lower priority than the periodic RT data packets, so they will not interfere with the transmission of RT packets during the scheduled time windows. In Fig. 5, the states of the gates that control the transmission of the periodic RT data packets and the non-scheduled (BE) traffic are also shown.

C. SOFT-HANDOVER ALGORITHM

As stated in Section II.C, the IEEE 802.11 standard-based handover algorithms proposed in the literature cannot carry out a handover process without interrupting the communication and are not suitable for critical industrial applications.

In order to solve this issue, an improved soft-handover algorithm is proposed that focuses on guaranteeing an uninterrupted communication during the handover process without the need for a second radio interface and with a reduced growth in network overhead. Moreover, in order to avoid any interruption in the communication, the proposed soft-handover algorithm, along with the proposed hybrid MAC protocol, assures that the wireless node that initiated the handover process (STA_H) will momentarily have time intervals assigned in the superframe of both, the current (AP_C) and target (AP_T) APs. To reduce the time needed to execute the handover, the MAC-level header of the RT data packets sent by the wireless nodes during the RT interval of the wireless MAC scheme will indicate the state of the handover process. Moreover, the proposed hybrid MAC scheme allow APs to exchange through the non-scheduled time windows of the TSN scheduler, the information related to the STA_H and the new scheduler that the STA_H must follow once the handover has been executed. In this way, the reliability of the process is increased.

Finally, the proposed algorithm does not require either a discovery phase or an authentication phase. This is because, in critical industrial applications, the nodes that form the hybrid network are preconfigured in advance, i.e. no external wireless nodes can be connected at the runtime. Hence, the number of APs and the basic information (the control cycle duration, the used radio channel, the authentication information etc.) are known beforehand.

The preparation and execution of the considered handover mechanism are divided into several phases which are detailed below.

1) COMMUNICATIONS BEFORE THE HANDOVER (PHASE 1)

At this point, the communication between the wireless node and the AP_C will follow the MAC scheme described in Section III.B.1. The nodes will exchange RT data packets periodically with the AP_C and vice versa. When a wireless node receives RT data packets sent by the AP_C, it should assess the quality of the link with the AP_C. If the quality of the link falls below a threshold for a predetermined time, the STA_H should look for a candidate AP (AP_N). This threshold will be used as a warning to a possible handover and will be the one that starts the second phase of the proposed handover process (Fig. 6). The intention of the STA_H to find an AP_N will be notified to its AP_C through the HO field ($HO = 2$) of the header of its next periodic RT data packet, which will be transmitted during its UL slot.

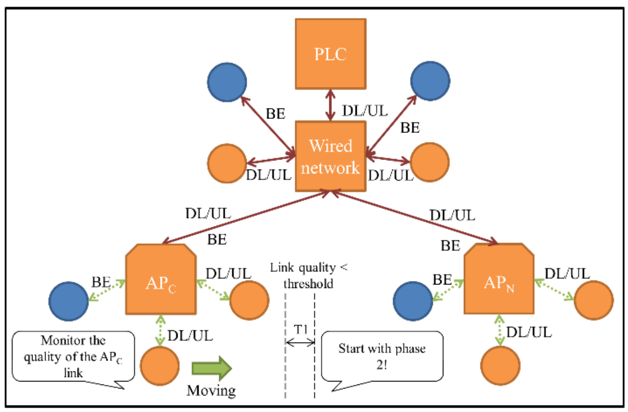

FIGURE 6. Communications before handover (Phase 1).

2) PRE-HANDOVER MEASUREMENTS (PHASE 2)

When the AP_C receives the intention of the STA_H to find an AP_N, it will send several parameters related to one AP_N to the STA_H through the HO field of the header of its next DL RT data packet. The shared information includes both the channel that the AP_N is using and its MAC address. Given that the DL packets are acknowledged, the AP_C will know if the STA_H has received the channel to sense.

In the affirmative case, the AP_C will notify the AP_N, through communications during non-scheduled time windows of the TSN scheduler, that it must occupy the following defined BE intervals of the proposed wireless MAC scheme sending Clear-To-Send (CTS) packets. In this way, the STA_H can evaluate the quality of the AP_N link by listening to the CTS packets sent by the AP_N. Given the possibility of fading due to variations in the channel, several BE periods of the proposed wireless MAC scheme may be necessary to estimate the quality of the link.

Note that, it may be the case that the AP_C assigns the STA_H an AP_N to sense that is not within the range of the STA_H. To solve this problem, first, the APs will be placed in such a way that an AP only has neighbors in non-overlapping channels. Then, if the STA_H does not receive any CTS packet during the BE interval of the proposed wireless MAC scheme, it will notify it to the AP_C through the HO field of the next periodic RT data packet sent during its UL slot, and the AP_C will send to the STA_H the channel of its other AP_N. In this way, regardless of where the STA_H is located, it will find an AP_N to sense. The information exchanged during this handover phase is represented through Algorithm 1. Note that, in the case of wireless segments, the information related to the handover is exchanged through the HO field of the RT data packets sent during the RT period of the proposed wireless MAC.

Algorithm 1 Pre-Handover Measurements.

1) The AP_Creceives the intention of the STA_H to find an AP_N:
   - 1.1) Wait until wireless DL phase.
   - 1.2) If it is the second time in step 1) during the same handover process:
     - 1.2.1) Notify the previous selected AP_N to stop sending CTS.
2) If DL slot assigned to STA_H:
   - 2.1) Send information to STA_H from one of its neighbor AP_N
   - 2.2) Wait until ACK packet.
3) If
   - 3-1) an ACK is received:
     - 3.1.1) AP_C notifies $AP_N$to occupy sending CTS packets the following wireless BE.
     - 3.1.2) Wait until the wireless BE interval.
     - 3.1.3) a NACK or no response is received: Go to step 2).
4) If BE interval of the wireless superframe:
   - 4.1) AP_N: send CTSs. STA_H: listen to the wireless medium.
   - 4.2) If STA_H receives CTSs:
     - 4.3.1) Repeat step 5) several times. Then go to phase 3 of the handover process.
   - 4.3) If STA_H does not receive CTSs:
     - 4.4.1) Notify the AP_C.
     - 4.4.2) Go to step 1) → the AP_C will send information to STA_H from its other neighbor AP_N.

3) HANDOVER DECISION (PHASE 3)

As shown in Fig. 7, a node will decide to carry out a handover if the quality of the AP_N link exceeds the AP_C link quality for a certain time as stated in (5). At this point, the AP_N becomes the AP_T with which the STA_H wants to associate.

$$Link_N - Hyst > Link_C + Off. \quad (5)$$

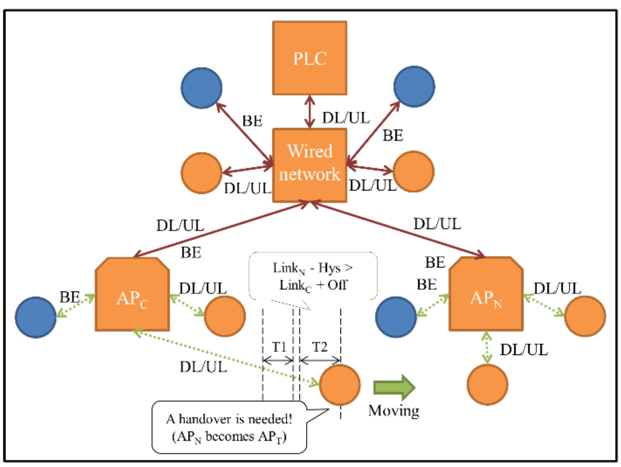

FIGURE 7. Communications during handover decision (Phase 3).

$Link_N$ and *$Link_C$* correspond to quality measurements of the AP_N and AP_C links respectively. A hysteresis (*Hyst*) and an offset (*Off*) values are considered to ensure that the handover will improve the link quality and to avoid ping-pong effect.

Regarding the variables measured the quality of the link, we have only contemplated mean Received Signal Strength Indicator (RSSI), but other metrics, such as channel statistics or Packet Error Rate (PER), can be considered. The achievable throughput that a mobile node could obtain can also be considered as done in [49]. These metrics may be analyzed in future improvements of the algorithm.

4) PREPARATION OF THE HANDOVER PROCESS (PHASE 4)

In the fourth phase, the STA_H must notify the decision to make a handover to the AP_C setting the state of the handover process in the HO field of the next UL RT data packet. When the AP_C receives this information, it will notify the AP_T that there is a STA_H that wishes to associate with it. This notification is transmitted during non-scheduled time windows of TSN scheduler.

Note that, in order not to compromise the operation of the system, the network must be dimensioned so that an AP can host all the nodes that form the wireless network. Although this entails an overgrowth of the wireless superframe, it also guarantees that an AP is able to manage all wireless nodes given an overload situation. That is why an AP_T will never reject a handover request.

Moreover, to maintain the backward compatibility with the IEEE 802.11 standard, once the AP_T realizes that there is a STA_H that wants to associate with it, the AP_T must send itself an association request primitive. At this point, the STA_H will be associated with it but it will not be able to communicate with it yet. Moreover, the AP_T should recalculate the scheduler to be able to assign slots to the STA_H and inform the other STAs associated accordingly. As stated in Section III.B.1, the transmission of the changes in the scheduler by an AP will be made during the BE period of the proposed wireless superframe and the transmission is immediate, without waiting for a contention.

Once all the nodes associated with the AP_T are aware of the change in the scheduler, the STA_H will still be associated with the AP_C; but it will have all the information of the AP_T and will be waiting to receive its new scheduler to finish with the association process. Finally, the AP_T will send a last packet to the AP_C, through the non-scheduled time windows of the TSN scheduler, indicating the scheduler that the STA_H must follow when the execution of the handover finishes.

5) HANDOVER EXECUTION (PHASE 5)

At this point, the AP_T must send the scheduler to the STA_H during the BE phase of the wireless superframe. When the STA_H receives the AP_T's scheduling information, it will momentarily have one DL and one UL slot assigned in the superframe of both AP_C and AP_T. Hence, the STA_H must be able to exchange the information related to the AP without interrupting the communication. Despite having slots assigned in both APs' superframes, the STA_H will only communicate with one of them. This depends on whether the STA_H has received the scheduler sent by the AP_T through the AP_C. To prevent unnecessary retransmissions, if the STA_H has not correctly received the AP_T's scheduler, the latter will not ask to retransmit a packet if the STA_H has communicated correctly with the AP_C and vice versa. That is, if STA_H has not yet received correctly the new scheduler, the AP_T will not ask it to retransmit a packet if the STA_H has communicated correctly with the AP_C. In this case, the AP_C will inform about the successful reception of the STA_H's packet to the AP_T through the non-scheduled time windows of the TSN scheduler. Similarly, if STA_H is communicating correctly with the AP_T, the latter will inform about the successful reception to the AP_C through the non-scheduled time windows of the TSN scheduler.

Finally, when the STA_H receives the AP_T's scheduler, it must confirm the reception of the new scheduler to its AP_C. This confirmation will be again carried out during the period dedicated to the transmission of BE traffic of the proposed wireless MAC scheme. Both the STA_H and the AP_C will continue using the AP_C scheduler until the DL interval of the next superframe ends. This is necessary because the scheduler that follows the wired nodes remains unchanged, and the packets sent by the STA_H to the PLC and vice versa are still transmitted through the AP_C. As soon as the DL interval ends, the STA_H will no longer be associated with the AP_C. The AP with which the STA_H will be associated from now on is the AP_T. Moreover, the STA_H will no longer have time slots assigned in the AP_C's superframe and will only communicate with the AP_T.

As explained before in the fourth phase of the proposed handover algorithm, to maintain the backward compatibility with IEEE 802.11 standard, the AP_C must send itself a disassociation request primitive. From this point onwards, the AP_T will become the AP_C of the STA_H and the one that was the AP_C will become an AP_N.

Finally, it will again be necessary to perform a reschedule on the AP that was the AP_C and this one must notify the wired network about the new change in the schedulers of the superframes. At this point, the handover process will have concluded as shown in Fig. 8.

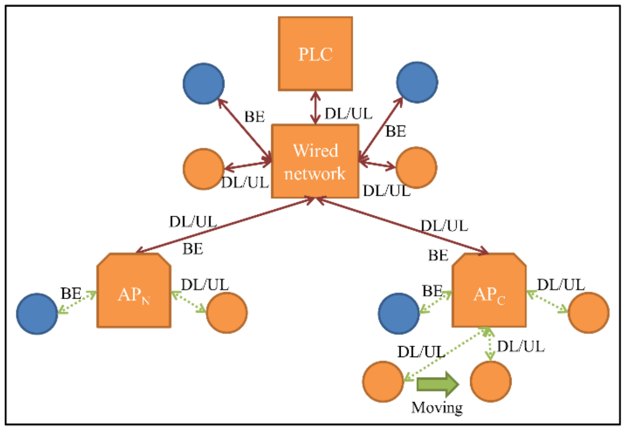

FIGURE 8. Communications after a handover.

IV. THEORETICAL ANALYSIS

A theoretical analysis has been carried out to study the validity of the proposed hybrid architecture described in Section III. This theoretical analysis provides the theoretical upper bounds for the MAC-to-MAC delay of the exchanged periodic RT traffic, assuming worst-case conditions. These bounds show whether a deterministic RT performance can be guaranteed or not with the proposed hybrid architecture. In addition, in the following analysis, the delays introduced by the TSN network and the PLC are neglected because they are supposed so fast that their effect is transparent to the wireless network.

As previously described, the traffic exchanged between the wired and wireless network are mostly periodic RT data packets. By means of the proposed hybrid architecture in Section III.B, the periodic RT data packets are transmitted deterministically and in an orderly way. Although BE traffic and changes in the scheduler due to a handover can also be transmitted with the proposed hybrid architecture, several mechanisms have been defined in Section III.B in order to prevent from colliding with the transmissions of the periodic

RT data packets. Moreover, both BE traffic and changes in the scheduler due to a handover can only be transmitted during the period of BE or during the retransmission slots if these remain unused (only in the case of the wireless network).

When calculating the upper bounds for the MAC-to-MAC delay, the structure of the proposed superframe must be considered to determine the minimum RT data flow that can be guaranteed through the considered wireless MAC. Considering the wireless TDMA scheme described in Section III.B.1, the total length of the superframe (c) is

$$c = t_{RT} + t_{BE}, \tag{6}$$

where t_{RT} is the time interval dedicated to transmitting/receiving the pre-scheduled RT data packets and t_{BE} is the time interval dedicated to transmitting BE information. Although, both t_{RT} and t_{BE} will have a variable duration, the duration of the superframe is always the same. As for the case of t_{RT}, this variability is given by both, the number of wireless nodes associated with each AP and by the number of retransmission slots (both DL and UL) required in each superframe. Therefore, t_{RT} can be defined as

$$t_{RT} = t_{DL} + t_{DLRetr} + t_{UL} + t_{ULRetr}, \tag{7}$$

where t_{DL} and t_{UL} correspond to the time interval required to transmit the DL/UL RT data packets of all the nodes associated with an AP, while t_{DLRetr} and t_{ULRetr} represent the time interval dedicated to the DL and UL retransmissions, respectively. Moreover, since the packets in industrial control applications are periodically generated, we can characterize the traffic arrival (α) in the uplink phase, $\alpha_{UL}(t)$, and in the downlink phase, $\alpha_{DL}(t)$, of the analyzed wireless MAC scheme as

$$\alpha(t) = \alpha_{UL}(t) + \alpha_{DL}(t), \tag{8}$$

$$\alpha_{UL}(t) = L\left\lceil \frac{t}{T} \right\rceil, \alpha_{DL}(t) = L\left\lceil \frac{t - Offset_{DL}}{T} \right\rceil, \tag{9}$$

$$Offset_{DL}(t) = t_{UL} + t_{ULRetr} + t_{BE}, \tag{10}$$

$$Offset_{UL}(t) = t_{DL} + t_{DLRetr}, \tag{11}$$

where T is the RT packet period, L the length of the RT packets and $Offset_{DL}$ and $Offset_{UL}$ are the offsets between the generation of the DL and UL traffic, respectively.

Although the traffic generation in all the nodes happens at the same moment with the proposed hybrid architecture, the network availability (β) will depend on when the retransmission of the packets is carried out. The cases shown in Table 2 have been considered in this analysis.

Hence, network availability in the uplink phase β_{UL} (t) and in the downlink β_{DL} (t) and the delays obtained in each of the considered cases are shown in Table 3. Note that, the MAC-to-MAC delay (d_{Total}) is divided into UL delay (d_{UL}) and DL delay (d_{DL}). The former is further divided into the time interval in which the node cannot transmit in UL interval (d_{UL1}) and the period in which the node can transmit in UL interval (d_{UL2}). In contrast, d_{DL} is divided into the time interval in which the node cannot transmit in DL interval (d_{DL1}) and the interval in which the node can transmit in DL interval (d_{DL1}). Finally, B represents the transmission capacity of the link.

TABLE 2. Analyzed retransmission cases.

Case	Description
1	Only one node needs to retransmit both DL/UL traffic and it has the whole-time interval dedicated to DL/UL retransmissions to do it.
2	Only one node needs to retransmit both DL/UL traffic and it has the whole-time interval dedicated to DL retransmissions to do it.
3	Only one node needs to retransmit both DL/UL traffic and it has the whole-time interval dedicated to UL retransmissions to do it.
4	The node cannot make retransmissions in the time interval dedicated to it.

TABLE 3. Obtained network availability and delay equations.

Case	Equations
All	$\beta(t) = \beta_{UL}(t) + \beta_{DL}(t)$
All	$d_{Total} = d_{UL} + d_{DL} = (d_{UL1} + d_{UL2}) + (d_{DL1} + d_{DL2})$
1, 3	$\beta_{UL}(t) = B \times max(\left\lfloor \frac{t + Offset_{UL}}{c} \right\rfloor \times (tslot_{UL} + t_{ULRetr}),$ $(t + Offset_{UL}) - \left\lceil \frac{t+Offset_{UL}}{c} \right\rceil \times (c - tslot_{UL} - t_{ULRetr}))$
1, 2	$\beta_{DL}(t) = B \times max(\left\lfloor \frac{t}{c} \right\rfloor \times (tslot_{DL} + t_{DLRetr}),$ $t - \left\lceil \frac{t}{c} \right\rceil \times (c - tslot_{DL} - t_{DLRetr}))$
2, 4	$\beta_{UL}(t) = B \times max(\left\lfloor \frac{t + Offset_{UL}}{c} \right\rfloor \times tslot_{UL},$ $(t + Offset_{UL}) - \left\lceil \frac{t+Offset_{UL}}{c} \right\rceil \times (c - tslot_{UL}))$
3, 4	$\beta_{DL}(t) = B \times max(\left\lfloor \frac{t}{c} \right\rfloor \times tslot_{DL},\ t - \left\lceil \frac{t}{c} \right\rceil \times (c - tslot_{DL}))$
1, 3	$d_{UL1} = Offset_{DL} - tslot_{UL} - t_{ULRetr}$ $d_{UL2} = tslot_{UL} + t_{ULRetr}$
1, 2	$d_{DL1} = Offset_{UL} - tslot_{DL} - t_{DLRetr}$ $d_{DL2} = tslot_{DL} + t_{DLRetr}$
2, 4	$d_{UL1} = Offset_{DL} - tslot_{UL}$ $d_{UL2} = tslot_{UL}$
3, 4	$d_{DL1} = Offset_{UL} - tslot_{DL}$ $d_{DL2} = tslot_{DL}$

Although the obtained network availability (β), both in UL and DL are different in the analyzed cases as shown in Table 3, the results obtained for the upper bound for the MAC-to-MAC-delay are the same in all the cases, which correspond to the duration of the proposed superframe (6). This delay is graphically shown in Fig. 9, taking into account the calculated network availability (β) and traffic arrival (α) for the case 1.

V. EVALUATION AND RESULTS

A. SIMULATION SETUP

The evaluation of the considered soft-handover algorithm along with the proposed hybrid TSN/IEEE 802.11 MAC scheme, both described in Section III, has been carried out through OMNeT++ 5.2.1 simulations. The wireless MAC scheme and the analyzed handover algorithm work on top

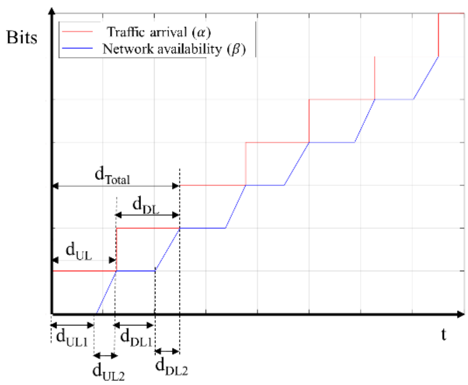

FIGURE 9. Obtained upper bound for the MAC-to-MAC delay in the case 1.

of the IEEE 802.11g OFDM physical layer. The obtained results focus on evaluating the performance of both the hybrid MAC scheme and the soft handover algorithm and they do not depend on the simulated physical layer. Hence, the obtained results are valid for any other physical layers.

The hybrid network architecture described in Section III.A has been considered to carry out the simulations, which consists of a PLC, 3 TSN switches, 3 APs (channel 1, 6 and 11) and 40 nodes. Because critical industrial applications consist of about 20 nodes [18], 20 nodes are considered for the wired segment and other 20 nodes for the wireless segment. Moreover, the wireless nodes will be mobile with a maximum speed of 30 km/h. This speed is taken as a reference in factory automation applications [18]. The nodes are placed randomly within a predefined area defined in OMNeT and they will be moving through it following random movement pattern. The RT data packets will be transmitted by the nodes periodically, having into account the control cycle of the application. In Table 4, the parameters of the simulated system are shown.

TABLE 4. Simulation parameters.

Simulated parameters	Wired network	Wireless network
Physical layer	IEEE 802.3	IEEE 802.11g ERP
Data rate	100 Mbps	24 Mbps
Noise threshold	-	-90 dBm
Industrial channel model	-	Ch1: rms delay spread of 58 ns Ch2: rms delay spread of 29 ns
Channel switching	-	7.5 µs
Control cycle	3.481 ms (1 superframe)	
Data payload	5 bytes	
Number of Retr slots	-	At least 5 for DL and 5 for UL
DL/DLRetr slot duration	8.64 µs (only DL)	69.75 µs
UL/ULRetr slot duration	8.64 µs (only UL)	35.75 µs (except the last UL) 69.75 µs (last UL and ULRetr)
BE slot duration	510.49 µs (1st) 453.99 µs (2nd)	At least 139.5 µs At most 1 superframe
SIFS	-	10 µs

As in [15], two industrial channels [50] have been simulated in combination with a small-scale fading model, which is dependent on the maximum Doppler shift. From now, the channels are going to be called Channel 1 (Ch1) and Channel 2 (Ch2). Both channels follow a Rayleigh distribution with non-line-of-sight (NLOS) conditions. While Ch1 has a rms delay spread of 58 ns, Ch 2 has a rms delay spread of 29 ns. Note that the Rayleigh fading on a channel with a shorter delay spread, leads to a higher deep-fading probability. That is why Ch 2 is more demanding than Ch 1.

For evaluating the performance of the analyzed soft-handover algorithm the average delay of the handover execution, the number of RT packet losses during the handover and the AP occupation have been evaluated. These analysis have been done taking into account several configuration setups, which involve the following parameters: a range of threshold values needed in the first phase of the considered handover algorithm (Table 5 , leftward) and a range of hysteresis (*Hyst*) and offset (*Off*) values needed in the third phase of the considered handover algorithm (Table 5, rightward). Different combinations of these three parameters have been considered in order to know which of them is the most influential.

TABLE 5. Simulated configurations (Regarding phase 1 threshold and *Hyst* and *Off* values).

Condition	Threshold: Rx power (dBm)	Threshold: PER
I	Ch1: -75	10^{-1}
	Ch2: -73	
II	Ch1: -72	10^{-2}
	Ch2: -69	
III	Ch1: -69	10^{-3}
	Ch2: -66	
IV	Ch1: -66	10^{-4}
	Ch2: -62	

Setup	*Hyst* (dB)	*Off* (dB)
1	0	0
2		2
3		4
4	2	0
5		2
6		4
7	4	0
8		2
9		4

Also, the analysis has been carried out without nodes with BE traffic to transmit and taking into account 20 nodes trying to transmit BE traffic per control cycle. The performance of the proposed soft-handover algorithm has also been compared with other algorithms proposed in the literature [28], [33]. Finally, to validate the performance of the proposed architecture, a comparison between the simulation results and the theoretical delay bounds obtained in Section IV is presented.

B. SIMULATION RESULTS

1) AVERAGE DELAY AND PACKETS LOSSES DURING THE HANDOVER

The performance of the proposed soft-handover algorithm described in Section III.C has been compared, in terms of average delay and packet losses during the handover process, with two other handover algorithms proposed in the literature [28], [33]. These two algorithms have been chosen because, although they do not completely avoid the interruption of the communication, they manage to reduce or eliminate the scanning phase, which is the most time-consuming phase of the entire standard handover process (≈ 90% of handover delay [51]).

Moreover, the analyzed handover algorithms have been combined with the hybrid MAC scheme described in Section III.B. For the evaluation of the handover execution delay in the studies proposed in [28], [33], only association and rescheduling phases have been considered. The triggering and scanning phases can be omitted because the algorithms force the node to change AP before the condition of the link deteriorates, and the decision to carry out the handover has not yet been made. Moreover, as defined Section III.C, no new STA_H/AP_T authentication is required during the handover execution because the devices in an industrial network are preconfigured and known in advance. In both algorithms, the criterion used to select the target AP is slightly different with respect to the one defined in the considered soft-handover algorithm. In this case, the offset value defined in (5) is not taken into account, as stated in [28], [33]. Finally, in both algorithms, the association phase of the IEEE 802.11 standard handover process is maintained.

In contrast, to assess the performance of the considered soft-handover mechanism, the first two phases have been omitted, because the decision to carry out the handover has not yet been made. In all the results, the handover is redefined as HO.

a: THE ANALYSED SOFT-HANDOVER ALGORITHM

The measured average delays and packet losses of the proposed soft-handover algorithm are shown in Table 6 and Table 7. In Table 8, an overview of the obtained average packet losses per handover can be seen.

TABLE 6. Analyzed soft-handover (under threshold conditions I and II).

Setup	Avg Pkt Losses per HO				Avg HO delay (normalized to the control cycle)			
	Condition I		Condition II		Condition I		Condition II	
	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2
1	1.133	1.003	0.0773	0.0794	6.82	5.84	4.79	4.81
2	0.919	0.796	0.0582	0.0598	5.76	4.74	3.77	3.78
3	0.749	0.584	0.0391	0.0404	4.72	3.76	2.76	2.77
4	1.157	0.987	0.0779	0.0807	6.79	5.82	4.81	4.82
5	0.938	0.784	0.0574	0.0595	5.73	4.72	3.71	3.73
6	0.726	0.573	0.0386	0.0407	4.7	3.78	2.77	2.79
7	1.165	0.998	0.0779	0.0804	6.78	5.8	4.79	4.81
8	0.931	0.772	0.0568	0.0603	5.72	4.71	3.71	3.73
9	0.717	0.564	0.0392	0.0399	4.71	3.77	2.78	2.81

First, unlike the algorithms proposed in [28], [33], with the considered soft-handover algorithm, the nodes trying to transmit BE traffic do not affect the handover execution at all. This is because the request and resolution of handover are included in the headers of the periodic RT data packets sent by the wireless nodes during the RT interval of the proposed wireless MAC scheme. In this way, the transmission of additional packets related to the handover process (e.g. for the association) is avoided during the BE period, as opposed

TABLE 7. Analyzed soft-handover (under threshold conditions III and IV).

Setup	Avg Pkt Losses per HO ($x10^{-3}$)				Avg HO delay (normalized to the control cycle)			
	Condition III		Condition IV		Condition III		Condition IV	
	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2
1	5.72	5.87	0.34	0.42	3.75	3.77	2.79	2.81
2	3.83	4.07	0.32	0.39	2.75	2.76	2.74	2.75
3	3.7	3.88	0.31	0.37	2.76	2.76	2.74	2.75
4	5.71	5.88	0.35	0.42	3.73	3.75	2.8	2.82
5	3.9	4	0.32	0.4	2.73	2.74	2.72	2.73
6	3.62	3.75	0.31	0.37	2.75	2.76	2.75	2.75
7	5.86	5.85	0.34	0.42	3.75	3.76	2.78	2.8
8	3.93	4.02	0.36	0.41	2.74	2.75	2.72	2.72
9	3.66	3.78	0.29	0.38	2.74	2.74	2.75	2.75

TABLE 8. Analyzed soft-handover overview.

Setup	Avg Pkt Losses per HO (in %)							
	Condition I		Condition II		Condition III		Condition IV	
	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2
1	8.72	9.12	0.859	0.882	0.082	0.084	0.0067	0.0084
2	8.36	8.84	0.831	0.854	0.077	0.081	0.0064	0.0079
3	8.32	8.34	0.782	0.807	0.074	0.078	0.0062	0.0074
4	8.9	8.97	0.866	0.897	0.082	0.084	0.0069	0.0084
5	8.52	8.71	0.82	0.85	0.078	0.08	0.0064	0.008
6	8.07	8.18	0.772	0.814	0.072	0.075	0.0062	0.0074
7	8.96	9.07	0.865	0.893	0.084	0.084	0.0068	0.0084
8	8.46	8.58	0.811	0.862	0.079	0.080	0.0071	0.0089
9	7.97	8.05	0.784	0.799	0.073	0.076	0.0058	0.0076

to the proposals under discussion. With the proposed soft-handover algorithm, during the handover, only the additional transmissions made between the AP and the node during the BE period are related to rescheduling. Moreover, it is shown that the obtained average delay, and consequently the packet losses, are very dependent on the selected hysteresis, offset and threshold values. On the one hand, the lower the threshold (condition I), the higher the packet losses and the average delay. The increase in the delay is because at lower threshold values, the AP_C/ STA_H link is very deteriorated and the STA_H will require more control cycles to execute the handover process. For the same reason, fewer handovers occur. On the other hand, the higher the value of the hysteresis and the offset, the lower the average delay is and less RT packets are lost. Since the channel changes as time advances, a node can be considered as an AP_N incorrectly, or the decision to look for an AP_N can be made when the link of the AP_C is deteriorated to the point of not being able to guarantee a correct communication. Both situations can arise by choosing incorrect offset and hysteresis values.

It must be considered that the threshold is the most critical parameter. For example, if the results obtained in condition II, III and IV of setup 9 are considered, the measured average delay is similar in all cases but the same cannot be said about the packet losses. While in the worst case (condition II) 0.784% and 0.799% of the RT packets are lost on average in Ch1 and Ch2, respectively, in the best case

TABLE 9. Average handover delay (threshold = -66 dBm, Off = 0 dB).

Hyst (dB)	Nº BE nodes	Avg HO delay (normalized to the control cycle)					
		Ch1			Ch2		
		[28]	[33]	Prop.	[28]	[33]	Prop.
0	0	9.58	7.96	3.77	10.76	8.56	2.79
	20	13.97	11.98		15.01	12.53	
2	0	8.94	7.46	3.75	9.85	8.06	2.8
	20	13.76	11.43		14.94	12.41	
4	0	8.81	7.37	3.76	9.76	7.98	2.78
	20	13.44	11.35		14.49	12.13	

TABLE 10. Average packet losses during the handover (Threshold = - 66 dBm, Off = 0 dB).

Hyst (dB)	Nº BE nodes	Avg Pkt Losses per HO					
		Ch1			Ch2		
		[28]	[33]	Prop.	[28]	[33]	Prop.
0	0	20	16	0.00034	22	18	0.00587
	20	28	24	(0.0067%)	30	26	(0.084%)
2	0	18	14	0.00035	20	16	0.00588
	20	28	22	(0.0069%)	30	24	(0.084%)
4	0	18	14	0.00034	20	16	0.00585
	20	26	22	(0.0068%)	28	24	(0.084%)

(condition IV), 0.0058% and 0.0076% of the RT packets are lost on average in Ch1 and Ch2, respectively. This is two orders lower. In contrast, for the same threshold value, only significant differences in the delay are shown. For example, if the results obtained in setups 1 and 9 of the condition I are considered, the average delay is about 35% lower in the case of setup 9 than in the case of setup 1, but the average RT packet losses are about 10% lower in the case of setup 9 than in the case of setup 1. Therefore, it can be concluded that the delay obtained is not entirely proportional to the packet losses.

Finally, the packet losses shown in Table 6, Table 7 and Table 8 are not due to the interruption of the communication of a node that has requested a handover (the communication is always maintained). The losses are due to the wireless channel itself.

b: COMPARISON

The performance of the proposed soft-handover algorithm has been compared with the handover algorithms in [28], [33] in terms of average delay and packet losses during the handover. The obtained results are shown in Table 9 and Table 10. The results are only shown for a threshold of -66 dBm because at higher threshold values, the results obtained for [28], [33] are similar, and at a lower threshold (< -66 dBm), the delay and the packet losses are increased due to the deterioration of the link.

Taking into account the structure of the superframe of the proposed wireless MAC scheme, the transmission and reception of the packets required in [28] for the proposed scanning phase and the association and rescheduling phases required in [28], [33] are relegated to the BE period. Therefore, this increases the time required to execute a handover, which becomes even more evident when the nodes trying to transmit BE traffic during this period are considered. These nodes will compete for access to the medium with the nodes that want to execute a handover. Moreover, because the proposal in [33] uses a second IEEE 802.11 interface to evaluate the link quality of the neighbor APs, the decision whether to execute the handover or not can be taken faster than in [28]. In the latter, the AP_C/STA_H link can be deteriorated enough to require more control cycles to execute the handover, and that is why the delay obtained in this case is higher than in [33]. On the one hand, regarding the packet losses, 100% of the RT data packets sent during the execution of the handover are lost in [28], [33], because the communication is completely interrupted during the handover. On the other hand, packet losses are less than 0.1% with the soft-handover algorithm described in Section III.C.

2) AP OCCUPATION

In addition to the average delay and the packet losses caused by the execution of the handover, the occupation of each AP has been measured, i.e. how many wireless nodes each AP has associated with it, on average. These results have been obtained only for the setups with the lowest percentage in terms of the average packet losses per handover (see Table 8). Thus, having an AP distribution and a mobility domain like the one shown in Fig. 10, the results related to the AP occupation are shown in Table 11 and Table 12. The simulated network is composed of 3 APs, called, AP0, AP1 and AP2 as shown in Fig. 10.

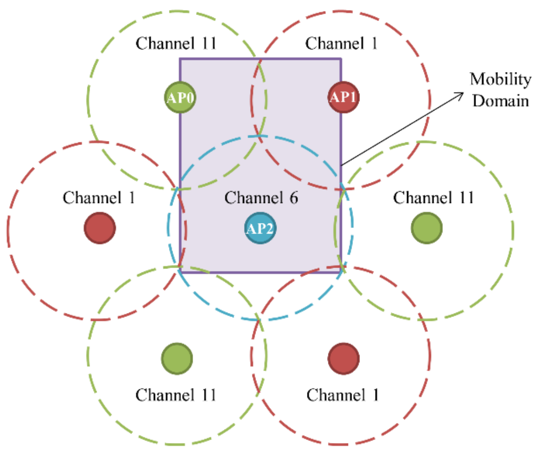

FIGURE 10. Simulated AP distribution and mobility domain.

TABLE 11. Average AP occupation under channel 1.

Condition	Associated wireless nodes on average		
	AP0	AP1	AP2
I	2	2	16
II	3	2	15
III	5	3	12
IV	5	5	10

TABLE 12. Average AP occupation under channel 2.

Condition	Associated wireless nodes on average		
	AP0	AP1	AP2
I	2	3	15
II	3	3	14
III	4	6	10
IV	5	6	9

The AP occupation is directly related to the number of handovers executed. Because in the simulation, the mobile nodes move randomly through the defined mobility domain, there is more area under the AP2 coverage range as shown in Fig. 10. Hence, as it is shown in Table 11 and Table 12 at low threshold values (condition I), the AP2 has more wireless nodes associated on average. In these cases, also fewer handovers occur as stated previously. In contrast, as the threshold value increases, and in consequence the number of handovers executed, the AP occupation is more equated.

3) MAC-TO-MAC DELAY

Finally, the Cumulative Distribution Function (CDF) of the MAC-to-MAC delays of the whole control cycle (comprising the transmission of both UL and DL traffic) has been calculated. It has been measured only for the setups with the lowest percentage in terms of the average packet losses per handover (see Table 8). The results of the minimum, maximum and average MAC-to-MAC delays are shown in Fig. 11 and Fig. 12.

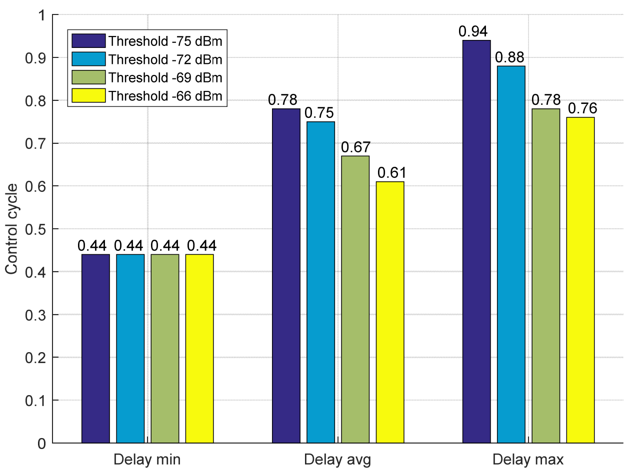

FIGURE 11. MAC-to-MAC delay under channel 1.

According to the results, for every setup, the calculated theoretical bounds in Section IV match with the simulation-based MAC-to-MAC delays. In none of the cases, the maximum MAC-to-MAC delay is greater than the theoretical bound, which corresponds to the length of the proposed wireless superframe, as stated in Section IV, i.e. the duration of the control cycle. The 100% of the packets arrive at the receiver after waiting to access the medium a maximum of 94% and 97% of the duration of one control cycle for Ch1 and Ch2, respectively.

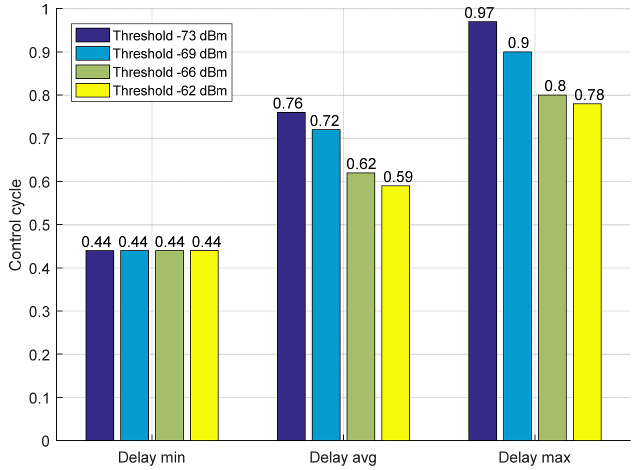

FIGURE 12. MAC-to-MAC delay under channel 2.

Moreover, as concluded in Section IV, it is not relevant when the periodic UL RT data packet is received within the UL interval of the wireless superframe. Regardless of whether the UL packet is received during the first UL slot or during the last ULRetr slot, for the calculation of the MAC-to-MAC delays of the whole cycle, the full UL interval must be taken into account. In the same way, the BE interval must be taken also into account when evaluating the MAC-to-MAC delay. This time period is defined previously in (10) as $Offset_{DL}$.

Taking this into account, the minimum MAC-to-MAC delay is given in the case in which a node receives its corresponding periodic DL RT data packet during the first slot dedicated to this purpose. Finally, in the cases where there is a predominant AP associated with most of the nodes that form the network (condition I), the obtained averaged MAC-to-MAC delay is higher.

VI. CONCLUSION

In this paper, a hybrid wired/wireless centralized architecture designed for industrial control applications is proposed, besides from expanding the wired network used in those applications to a wireless domain. While TSN technology has been selected to control the wired segment, a MAC scheme based on the IEEE 802.11 physical layer is proposed in order to control the wireless network. This hybrid architecture has deterministic and RT features in order to ensure the requirements of industrial control application. This hybrid scheme ensures a seamless communication between both media through an AP. The proposed architecture includes a soft-handover algorithm designed to guarantees an uninterrupted communication during its execution. This mechanism allows to expand the application area and obtain even more benefits from using wireless communications. A theoretical analysis has been carried out to study the validity of the proposed hybrid architecture, and new results are presented in order to evaluate the performance of the proposed soft-handover mechanism thoroughly in combination with defined hybrid wireless/wired network architecture.

The performance of the proposed soft-handover algorithm is compared with other handover algorithms proposed in some recent studies in terms of average delay and RT packet losses during the handover process. The evaluation of the proposed architecture has been carried out through OMNeT++ simulations and using realistic industrial channel models.

The results show that the proposed soft-handover algorithm guarantees seamless communication during the handover process, unlike the other analyzed state-of-the-art handover algorithms. In these studies, 100% of the RT data packets sent during the execution of the handover were lost, because the communication between the AP/node was completely interrupted. In contrast, with the proposed soft-handover algorithm, the communication between the AP/node is maintained during the whole handover process because the proposed soft-handover algorithm, along with the proposed hybrid MAC protocol, assures that the node will momentarily have slots in both the current and target APs. Moreover, it is shown that the obtained average delay during the handover execution and packet losses are very dependent on the selected handover parameters (hysteresis, offset and threshold values). It is shown that the obtained average MAC-to-MAC delay is not only conditioned by the number of wireless nodes associated with an AP, but it is also dependent on the number of slots required to perform retransmissions.

Finally, several aspects will be addressed in future improvements of the proposed hybrid architecture. Firstly, regarding the variables that measure the quality of the link when the handover decision is taken, we have only contemplated mean RSSI, but other metrics, such as channel statistics or PER, can be considered. These metrics will be analyzed in future improvements of the algorithm.

Secondly, a rate adaptation algorithm will be included in the proposed hybrid MAC to determine the optimal data transmission rate according to the conditions of the wireless channel.

Thirdly, the study of the RT performance of the proposed hybrid centralized architecture will be extended to event-triggered traffic related to safety-critical messages.

Finally, the considered soft-handover algorithm will be integrated into future versions of SHARP, a novel hybrid network specially designed to guarantee the 1 ms control cycle required by most critical industrial applications.

REFERENCES

[1] M. Ehrlich, L. Wisniewski, and J. Jasperneite, "State of the art and future applications of industrial wireless sensor networks," in *Kommunikation und Bildverarbeitung in der Automation* (Technologien für die intelligente Automation). Berlin, Germany: Springer, 2018, pp. 28–39.

[2] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin, "Smart factory of industry 4.0: Key technologies, application case, and challenges," *IEEE Access*, vol. 6, pp. 6505–6519, 2017.

[3] M. Raza, N. Aslam, H. Le-Minh, S. Hussain, Y. Cao, and N. M. Khan, "A critical analysis of research potential, challenges, and future directives in industrial wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 39–95, 1st Quart., 2018.

[4] W. Shen, T. Zhang, F. Barac, and M. Gidlund, "PriorityMAC: A priority-enhanced MAC protocol for critical traffic in industrial wireless sensor and actuator networks," *IEEE Trans. Ind. Informat.*, vol. 10, no. 1, pp. 824–835, Feb. 2014.

[5] T. Zhong, C. Mengjin, Z. Peng, and W. Hong, "Real-time communication in WIA-PA industrial wireless networks," in *Proc. 3rd Int. Conf. Comput. Sci. Inf. Technol. (ICCSIT)*, Jul. 2010, pp. 600–605.

[6] P. Suriyachai, U. Roedig, and A. Scott, "A survey of MAC protocols for mission-critical applications in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 2, pp. 240–264, 2nd Quart., 2012.

[7] M. Gidlund, T. Lennvall, and J. Åkerberg, "Will 5G become yet another wireless technology for industrial automation?" in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2017, pp. 1319–1324.

[8] Z. Ma, M. Xiao, Y. Xiao, Z. Pang, H. V. Poor, and B. Vucetic, "High-reliability and low-latency wireless communication for Internet of Things: Challenges, fundamentals and enabling technologies," *IEEE Internet Things J.*, to be published.

[9] V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4258–4265, Oct. 2009.

[10] S. Dietrich, G. May, J. von Hoyningen-Huene, A. Mueller, and G. Fohler, "Frame conversion schemes for cascaded wired / wireless communication networks of factory automation," *Mobile Netw. Appl.*, vol. 23, no. 4, pp. 817–827, 2017.

[11] S. Zoppi, A. V. Bemten, H. M. Gürsu, M. Vilgelm, J. Guck, and W. Kellerer, "Achieving hybrid wired/wireless industrial networks with WDetServ: Reliability-based scheduling for delay guarantees," *IEEE Trans. Ind. Informat.*, vol. 14, no. 5, pp. 2307–2319, May 2018.

[12] C. Cruces, R. Torrego, A. Arriola, and I. Val, "Deterministic hybrid architecture with time sensitive network and wireless capabilities," in *Proc. IEEE 23rd Int. Conf. Emerg. Technol. Factory Automat. (ETFA)*, Sep. 2018, pp. 1119–1122.

[13] Y. Luo, Y. Duan, W. Li, P. Pace, and G. Fortino, "A novel mobile and hierarchical data transmission architecture for smart factories," *IEEE Trans. Ind. Informat.*, vol. 14, no. 8, pp. 3534–3546, Aug. 2018.

[14] H. Zhang and L. Dai, "Mobility prediction: A survey on state-of-the-art schemes and future applications," *IEEE Access*, vol. 7, pp. 802–822, 2018.

[15] Z. Fernández, Ó. Seijo, I. Val, and M. Mendicute, "Soft-handover algorithm for hybrid industrial wireless sensor and actuator networks," in *Proc. IEEE 23rd Int. Conf. Emerg. Technol. Factory Automat. (ETFA)*, Sep. 2018, pp. 282–289.

[16] S. Dietrich, G. May, O. Wetter, H. Heeren, and G. Fohler, "Performance indicators and use case analysis for wireless networks in factory automation," in *Proc. IEEE Conf. Emerg. Technol. Factory Automat. (ETFA)*, Sep. 2017, pp. 1–8.

[17] M. C. Lucas-Estañ, M. Sepulcre, T. P. Raptis, A. Passarella, and M. Conti, "Emerging trends in hybrid wireless communication and data management for the industry 4.0," *Electronics*, vol. 7, no. 12, p. 400, 2018.

[18] P. Schulz, M. Matthe, H. Klessig, M. Simsek, G. Fettweis, J. Ansari, S. A. Ashraf, B. Almeroth, J. Voigt, I. Riedel, A. Puschmann, A. Mitschele-Thiel, M. Müller, T. Elste, and M. Windisch, "Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 70–78, Feb. 2017.

[19] M. Luvisotto, Z. Pang, and D. Dzung, "High-performance wireless networks for industrial control applications: New targets and feasibility," *Proc. IEEE*, vol. 107, no. 6, pp. 1074–1093, Jun. 2019.

[20] H. Xu, W. Yu, D. Griffith, and N. Golmie, "A survey on industrial Internet of Things: A cyber-physical systems perspective," *IEEE Access*, vol. 6, pp. 78238–78259, 2018.

[21] H. Trsek and J. Jasperneite, "An isochronous medium access for real-time wireless communications in industrial automation systems—A use case for wireless clock synchronization," in *Proc. IEEE Int. Symp. Precis. Clock Synchronization Meas., Control Commun. (ISPCS)*, Sep. 2011, pp. 81–86.

[22] Ó. Seijo, Z. Fernández, I. Val, and J. A. López-Fernández, "SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks," in *Proc. 14th IEEE Int. Workshop Factory Commun. Syst. (WFCS)*, Jun. 2018, pp. 1–10.

[23] G. Cena, S. Scanzio, A. Valenzano, and C. Zunino, "An enhanced MAC to increase reliability in redundant Wi-Fi networks," in *Proc. 10th IEEE Workshop Factory Commun. Syst. (WFCS)*, May 2014, pp. 1–10.

[24] Y. Cheng, D. Yang, and H. Zhou, "Det-WiFi: A multihop TDMA MAC implementation for industrial deterministic applications based on commodity 802.11 hardware," *Wireless Commun. Mobile Comput.*, vol. 2017, Apr. 2017, Art. no. 4943691.

[25] H. Trsek, *Isochronous Wireless Network for Real-Time Communication in Industrial Automation*. Berlin, Germany: Springer, 2016, p. 182.

[26] P. G. Peón, E. Uhlemann, W. Steiner, and M. Björkman, "Medium access control for wireless networks with diverse time and safety real-time requirements," in *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2016, pp. 4665–4670.

[27] L. Leonardi, F. Battaglia, G. Patti, and L. L. Bello, "Industrial LoRa: A novel medium access strategy for LoRa in industry 4.0 applications," in *Proc. 44th Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 1, Oct. 2018, pp. 4141–4146.

[28] S. Feirer and T. Sauter, "Seamless handover in industrial WLAN using IEEE 802.11k," in *Proc. IEEE 26th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2017, pp. 1234–1239.

[29] A. A. Tabassam, H. Trsek, S. Heiss, and J. Jasperneite, "Fast and seamless handover for secure mobile industrial applications with 802.11r," in *Proc. IEEE 34th Conf. Local Comput. Netw. (LCN)*, Oct. 2009, pp. 750–757.

[30] P. Machań and J. Wozniak, "On the fast BSS transition algorithms in the IEEE 802.11r local area wireless networks," *Telecommun. Syst.*, vol. 52, no. 4, pp. 2713–2720, 2013.

[31] A. Zubow, S. Zehl, and A. Wolisz, "BIGAP—Seamless handover in high performance enterprise IEEE 802.11 networks," in *Proc. IEEE/IFIP Netw. Oper. Manage. Symp. (NOMS)*, Apr. 2016, pp. 445–453.

[32] Y. Kim, H. Choi, K. Hong, M. Joo, and J. Park, "Fast handoff by multi-beacon listening in IEEE 802.11 WLAN networks," in *Proc. 9th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2017, pp. 806–808.

[33] J.-P. Jeong, Y. D. Park, and Y.-J. Suh, "An efficient channel scanning scheme with dual-interfaces for seamless handoff in IEEE 802.11 WLANs," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 169–172, Jan. 2018.

[34] E. Zeljkovic, R. Riggio, and S. Latre, "Exploiting distance information for transparent access point driven Wi-Fi handovers," in *Proc. IEEE 18th Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2017, pp. 1–6.

[35] L. Wisniewski, H. Trsek, I. Dominguez-Jaimes, A. Nagy, R. Exel, and N. Kerö, "Location-based handover in cellular IEEE 802.11 networks for factory automation," in *Proc. IEEE 15th Conf. Emerg. Technol. Factory Automat. (ETFA)*, Sep. 2010, pp. 1–8.

[36] M. Y. Chan, S. Baroudi, J. Siu, and J. Liebeherr, "Measurement-based handover method for communication-based train control systems," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2017, pp. 1–6.

[37] B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf, J. Huschke, I. Aktas, and J. Ansari, "Wireless communication for factory automation: An opportunity for LTE and 5G systems," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 36–43, Jun. 2016.

[38] S. A. Ashraf, I. Aktas, E. Eriksson, K. W. Helmersson, and J. Ansari, "Ultra-reliable and low-latency communication for wireless factory automation: From LTE to 5G," in *Proc. IEEE 21st Int. Conf. Emerg. Technol. Factory Automat. (ETFA)*, Sep. 2016, pp. 1–8.

[39] L. C. Gimenez, M. C. Cascino, M. Stefan, K. I. Pedersen, and A. F. Cattoni, "Mobility performance in slow- and high-speed LTE real scenarios," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.

[40] *Requirements Related to Technical Performance for IMT-Advanced Radio Interfaces*, document M.2134-0, ITU, 2008.

[41] *Study on Latency Reduction Techniques for LTE*, document TR 36.881 V14.0.0, 3GPP, 2016, pp. 1–99.

[42] M. Lauridsen, L. C. Gimenez, I. Rodriguez, T. B. Sorensen, and P. Mogensen, "From LTE to 5G for connected mobility," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 156–162, Mar. 2017.

[43] X. Wu and H. Haas, "Handover skipping for LiFi," *IEEE Access*, vol. 7, pp. 38369–38378, 2019.

[44] L. Underberg, R. Kays, S. Dietrich, and G. Fohler, "Towards hybrid wired-wireless networks in industrial applications," in *Proc. IEEE Conf. Ind. Cyber-Phys. Syst. (ICPS)*, May 2018, pp. 768–773.

[45] Z. Fernandez, C. Cruces, I. Val, and M. Mendicute, "Deterministic MAC access control scheme for industrial hybrid IEEE 802.3/IEEE 802.11 networks," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2017, pp. 1–8.

[46] *IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems Local and Metropolitan area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11-2016, Dec. 2016.

[47] W. Steiner, P. G. Peón, M. Gutiérrez, A. Mehmed, G. Rodriguez-Navas, E. Lisova, and F. Pozo, "Next generation real-time networks based on IT technologies," in *Proc. IEEE 21st Int. Conf. Emerg. Technol. Factory Automat. (ETFA)*, Sep. 2016, pp. 1–8.

[48] *IEEE Standard for Local and Metropolitan Area Networks—Bridges and Bridged Networks—Amendment 25: Enhancements for Scheduled Traffic*, IEEE Standard 802.1Qbv-2015, Mar. 2016.

[49] M. Peng, G. He, L. Wang, and C. Kai, "AP selection scheme based on achievable throughputs in SDN-enabled WLANs," *IEEE Access*, vol. 7, pp. 4763–4772, 2018.

[50] R. Croonenbroeck, L. Underberg, A. Wulf, and R. Kays, "Measurements for the development of an enhanced model for wireless channels in industrial environments," in *Proc. IEEE 13th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2017, pp. 1–8.

[51] A. Mishra, M. Shin, and W. Arbaugh, "An empirical analysis of the IEEE 802.11 MAC layer handoff process," *ACM Comput. Commun. Rev.*, vol. 33, pp. 93–102, Apr. 2003.

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