SHARP: A Novel Hybrid Architecture for Industrial Wireless Sensor and Actuator Networks

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***Abstract*—Industrial communications have very challenging requirements, especially in Factory Automation (FA) scenarios. Some of these requirements are: packet deadline bounds, high reliability, low transmission jitter, and communication determinism. Wireless communications solutions offer significant advantages over wired solutions: lower costs, faster and seamless deployment, higher flexibility and scalability, and free movement of the systems communicated wirelessly. However, standard wireless technologies do not provide enough performance to satisfy all of the industrial communications requirements in most cases and, therefore, wired solutions cannot be directly replaced by wireless solutions. In this work, we present SHARP (Synchronous and Hybrid Architecture for Real-time Performance in IWSAN), a novel hybrid architecture specially designed for industrial automation, where Ultra-Reliable Low-Latency Communications (URLLC) are required. This paper is mainly focused on the wireless segment of SHARP, a wireless architecture that includes a physical layer based on 802.11g along with a Time Division Multiple Access (TDMA) Medium Access Control (MAC) layer to ensure communication determinism, while maintaining backward compatibility with 802.11. Wireless SHARP segment behavior and its performance are evaluated through OMNeT++ simulations.**

Keywords*—Industrial communications, Wireless communications, IEEE802.11, Industrial Wireless Sensor and Actuator Networks, Time-critical.

I. INTRODUCTION

Industrial Wireless Sensor and Actuator Networks (IWSAN) are defined as networks which connect multiple sensors and actuators wirelessly. The task of the sensors is to obtain information from the environment, which is sent to a controller, commonly a Programmable Logic Controller (PLC), in order to process it and to make decisions accordingly to the information received from the sensors. This information is sent to the actuators through the wireless network, which perform the requested task. Several potential IWSAN applications have real-time (RT) requirements, such as Factory Automation (FA) and Process Automation (PA), where closed-control loops are used. RT requirements are application dependent [1] and may be classified in three main groups:

- Temporal requirements: in closed-loop control applications, the temporal requirement is usually defined as a deadline bound inside a communication cycle, and can take values from 100 ms to 1 ms. In open loop applications, the requirements are usually defined as a maximum delay bound (from 100 to 1 ms) and a Latency (from 10 ms to 250 µs).
- Reliability requirements: reliability is usually defined as the Packet Loss Rate (PLR) at application level, which may be from 10^{-6} to 10^{-12}.
- Packet Rate and bit rate: these two requirements are set by the number of nodes and their payload size. The amount of nodes is variable from few nodes to more than 1000 nodes and the packet size may be from 10 bytes to up to 300 bytes.

There are some particular aspects of industrial communications that may be exploited to obtain a high performance in wireless communications. Some of them are: short packet length, periodic traffic, asymmetries in downlink (DL) and uplink (UL) and slow variation of the wireless transmission medium [2]. Furthermore, IWSAN requirements are aligned to the requirements in Ultra-Reliable Low-Latency Communications (URLLC), as one of the proposed scenarios for the use of URLLC is industrial automation.

The main wireless standards used in WSAN have been proposed to be used in IWSAN. These standards are: Zigbee [3], WirelessHART [4] and WIA-PA [5]. All of them are based on IEEE 802.15.4 PHY [6] and defines their own MAC to achieve different features. Zigbee uses a CSMA/CA based MAC, thus a time bound cannot be guaranteed due to collisions [3]. WirelessHART uses a TDMA access scheme, providing accurate packet transmission instants, but its reliability is not enough [7] and its bitrate is quite low [6]. Finally, WIA-PA standard lacks of a mechanism to support real-time communications with very low latency [8].

There are some proposals in the literature which fulfills some of the requirements of the IWSAN networks in Factory Automation. For example, IsoMAC [9] is a wireless architecture based on 802.11g and a TDMA based MAC layer which fulfills a communication cycle of 4 ms and a medium bitrate. However, IsoMAC is still far away from a communication cycle of 1 ms and cannot manage a high

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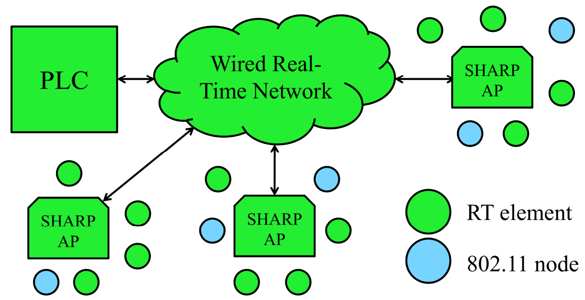

Fig. 1. SHARP network topology.

number of nodes [10]. Furthermore, we have found in previous works that 802.11g standard plus a TDMA MAC can be used to achieve 1 ms communication cycle [11]. However, the results show that it could only support up to 4 RT nodes with a Packet Error Rate (PER) of 10^{-4} over a channel with 30 dB of Signal to Noise Ratio (SNR) and Rayleigh fading.

In order to make wireless technology to be suitable to its use in industrial scenarios with high communications requirements, a novel hybrid architecture, named SHARP (Synchronous and Hybrid Architecture for Real-time Performance in IWSAN), is outlined in this paper. The paper is focused on the description of the wireless segment of SHARP (Wireless SHARP), while the full SHARP architecture will be detailed in future works.

Wireless SHARP is based on a modification of the 802.11g OFDM PHY layer along with a TDMA MAC. Wireless segment main features are: i) communication determinism, ii) high reliability (PLR<10^{-8} under a realistic industrial channel), iii) high packet rate (it supports up to 40 wireless RT nodes with a control cycle of 1 ms) and iv) low bandwidth (20 MHz). Furthermore, it maintains compatibility with 802.11, due to the use of some standard mechanisms to guarantee the 802.11 nodes can gain the access to the radio medium without interfering RT transmissions.

The rest of the article is organized as follows: First, the proposed system is described in section II. In section III, the simulation scenario used to show the system behavior is described. Performance results obtained through OMNeT++ simulations are shown in Section IV. Finally, Section V concludes the article.

II. Wireless SHARP Description

Wireless SHARP is a wireless architecture especially designed for industrial scenarios with high performance requirements in terms of reliability, packet delay and communication cycle period. The fulfilling of these requirements is obtained through a custom architecture especially designed for these applications.

Regarding wireless SHARP network topology, it uses a star topology, with one wireless coordinator, named SHARP Access Point (SHARP AP), several slave nodes which support Wireless SHARP and some 802.11 nodes, as shown in Fig. 1.

Focusing on wireless technology, the MAC layer is based on a TDMA scheme to guarantee communication determinism and high reliability. The TDMA SuperFrame is split into two main periods, the RT period, reserved to RT packets, and the legacy period, used by standard nodes to transmit 802.11 frames. On the other hand, the PHY layer is based on 802.11g OFDM and uses three waveforms to greatly increase network bitrate: 802.11g OFDM waveform, a waveform for DL frames with PHY frame aggregation and a waveform for UL frames with a shortened preamble.

In order to maintain compatibility with 802.11 standard, a Best Effort (BE) period is defined in the TDMA. To ensure no legacy nodes transmit on the RT period, some mechanisms from 802.11 are used to deny legacy nodes to gain access of the radio channel.

Lastly, Wireless SHARP architecture offers great flexibility as the network is highly configurable, so it can be easily adapted to many applications and scenarios. Those parameters can be sent over the air at network initialization, thus there is no need of manually program every slave node. Some of them are:

- *Control cycle period.*
- *Packet Payload of each node.*
- *Frame Modulation and Coding Scheme (MCS) of each node.*
- *Number of DL nodes and number of UL nodes.*
- *Scheduling algorithm.*
- *Retransmission scheme.*
- *Enabling/Disabling compatibility with 802.11.*

A. Network Topology

The optimum network topology in IWSAN is application dependent. As an example, a mesh network is suitable when the delay requirement is low, but the network needs path redundancy and, in order to achieve a long lifetime, a low power consumption of the nodes is compulsory. However, in closed-loop control applications, where the control cycle period is low, a star network is more suitable, as the wireless coordinator schedules real-time packets in a more restrictive way. Furthermore, in a hybrid architecture, a wireless star topology offers an easy integration of the wireless and wired segments. Therefore, a star topology has been chosen as the best option to fulfill industrial automation requirements. A wireless network is compound of one SHARP AP, several slave nodes and some 802.11 legacy nodes that are used to perform low bit-rate tasks such as network monitoring, remote control, IoT nodes, etc.

A full SHARP network has a network control center coordinator (PLC), an RT wired network, multiple SHARP APs connected by an RT wired network, and finally, several nodes connected to the SHARP APs wirelessly (Fig. 1). In addition, some slave nodes also can be connected to the RT network by wired connection. The wired segment should be built with an RT wired standard, e.g. Time Sensitive Networking (TSN) [12], to ensure a fast packet delivering between the network elements. In this article we assume the wired RT network and PLC to be fast enough to presume the delays introduced by their operation are null, so it is transparent to the wireless network.

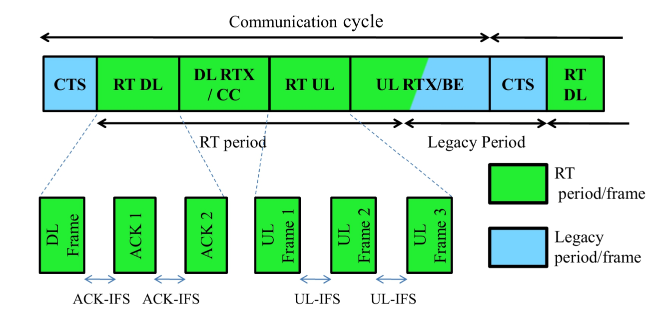

Fig. 2. TDMA SuperFrame.

A SHARP AP acts as a bridge between the wireless segment and the wired segment through routing the packets from the wired network to the wireless network and vice versa. Furthermore, A SHARP AP performs the network management, while slave nodes tasks are retrieving scheduling information from the SHARP AP and acts consequently sending or receiving packets in the indicated instants. This master-slave structure has two main advantages: i) slave nodes are simple, as their only duty is sending and receiving frames based on the schedule information received from the AP, and ii) The AP holds all the network information, so it can take very quick decisions about changes in the network scheduler and propagate these decisions to the slave nodes.

B. MAC layer definition

The MAC layer uses a TDMA specially designed to exploit, in combination with the PHY, the slow variation of the industrial wireless communications channel and the industrial traffic characteristics.

The TDMA SuperFrame is divided in two periods: RT period and Best Effort period. The Best Effort period is used by 802.11 legacy stations to transmit no RT information, hence using 802.11 standard, while the traffic of the RT period follows the proposed wireless technology. The start of the SuperFrame is the transmission of the Clear To Send (CTS) frame [13] and the duration of a SuperFrame (noted as t_{cycle}) is defined as the time between two CTS frames. The SuperFrame structure is shown in Fig. 2.

To ensure a correct performance of the TDMA scheme, the system must deliver a very high precision clock to every node of the wireless network. We have shown in [14] through real measurements that Precision Time Protocol (PTP) [15] over 802.11g can be used to distribute a clock with an accuracy as small as 30 ns which is enough for the application.

The RT period is based on a semi-persistent scheduler, which is generated by the SHARP AP and includes the transmission instant of every RT frame and ACK, and their respective MCS and payload length. This information is propagated to the slave nodes at network initialization and may be modified through Control Channel (CC) at runtime to easily adapt the system to channel variations. It should be noted that slave nodes do not need to have the scheduling information of every node, but only their scheduling information (their instants of transmission and reception, major changes in the scheduler, etc.).

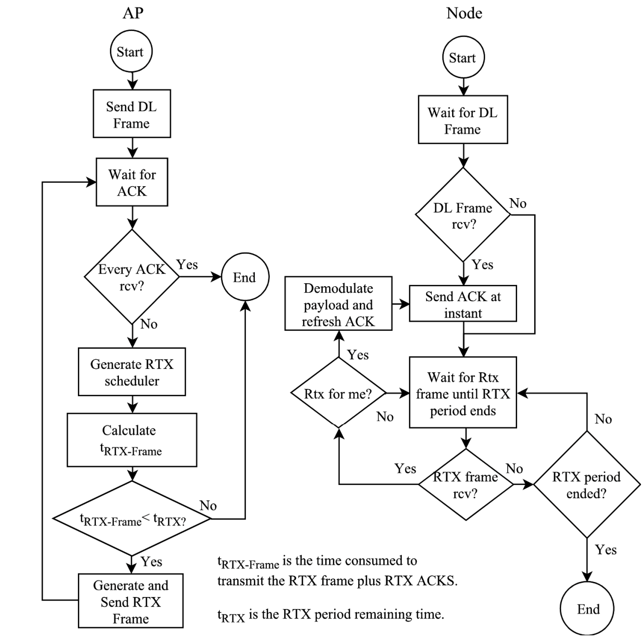

Fig. 3. DL retransmission flowchart.

The RT period is in turn divided into multiple RT slots, which are described below.

1) CTS-to-self frame

A communication cycle starts with a 802.11 CTS-to-Self frame [13]. This frame is used to deny legacy nodes to transmit during the RT period by setting their Network Allocation Vector (NAV) [13] to the duration value specified in the CTS frame. This mechanism is further explained in Section II.*D*.

2) Real-Time Downlink (RT DL)

RT packets transmitted from the SHARP AP to the slave nodes are transmitted during this period. RT DL packets are grouped with PHY frame aggregation, using the waveform proposed in section II.*C.2)*. The first packet of the RT DL period is always an RT-beacon frame with MCS = 0 (BPSK modulation with ½ convolutional code), which carries network basic information and a packet timestamp for clock synchronization. Each node knows the position of its payload inside the DL frame, and its length and MCS, so they only need to detect the DL frame, synchronize its receiver and demodulate the pertinent portion of the frame.

Once the DL frame is transmitted, slave nodes must return an ACK if they received their corresponding payload at the instant indicated in the scheduler. ACKs are sent in a row using the UL waveform, which is described in section II.*C.3)*. A scheme of an RT DL period is shown in Fig. 2.

3) Downlink Retransmissions and Control Channel (DL RTx/CC)

This period has three main tasks: retransmit RT packets of the DL period, send changes in the scheduling information and do general monitoring tasks.

If the AP does not receive every expected ACK, it must send a retransmission packet that contains the scheduling information of the retransmission and the DL payloads. The scheduling information contains the ID of the nodes that must listen for the retransmission, the position of each RTx payload, its MCS, and the transmission instant of each ACK. Fig. 3 represents the process done in a DL retransmission.

This process is carried out until the *DL RTx/CC* period is over or until every ACK has been received successfully. Once the RTx task is over, the AP must check each channel (DL or UL) to verify that every MCS is appropriate to the characteristics of the communication channel (PER/ frames Rx Power). If not, it can reschedule the RT frames to reduce or increase frame MCS to optimize consumed airtime or PER. Finally, the AP can poll the slave nodes to retrieve their status information.

If none of these operations is done in the actual SuperFrame, the DL RTx/CC will be empty.

4) Real-Time Uplink (RT UL)

RT packets from the slave nodes to the SHARP AP are transmitted during this period using the waveform described in section II C.3).

RT UL frames are sent in a row one after another with a very precise timing. The transmission instant, length and MCS of each UL frame are preset during network initialization and known by the SHARP AP. To ensure a high efficiency, the InterFrame Space (IFS) between them must be small. UL period is represented in Fig. 2.

RT UL frames from slave nodes carry data from their sensors that is only relevant to the PLC so they do not need to know if the data has been correctly delivered. As the slave nodes are only allowed to transmit in the time slots pre-assigned by the AP, there is no need of ACK in the UL period.

The start of the RT UL period is absolute inside each SuperFrame, and it does not depend on the DL periods configuration. However, its start point can be changed at runtime through a packet transmitted in the control channel.

5) Uplink Retransmissions and Best Effort (UL RTx/BE)

If an RT frame from the *RT UL* period is lost, the AP must send at the start of this period an RTx frame to the slave nodes as done in the *DL RTx/CC* period. The scheduling information in the RTx frame contains the node IDs that must retransmit a packet, their transmission instant and the modulation scheme of each packet.

When the Uplink Retransmissions phase is over, the remaining time of the period is used by 802.11 nodes to transmit legacy frames, thus ensuring compatibility with 802.11 standards. The legacy nodes may gain access to the medium through the standard access scheme, due to their NAV value is 0 µs at the end of the RT period and the channel is no more occupied by RT transmissions.

Best Effort period is further subdivided in two slots, a Non Controlled Phase (NCP) and a Controlled Phased (CP). In the NCP every 802.11 node is free to transmit, while in the CP the AP takes the control of the channel as soon as it can. This method, proposed in [16], is used to ensure none of the legacy frames invade the RT period and cause interferences. Its operation is described in section II.*D*.

C. PHY layer definition

1) 802.11 OFDM-based PHYs

Latest versions of IEEE 802.11 standards use OFDM modulation due to its robustness in time dispersive channels and spectrum efficiency [17]. First OFDM-based PHYs defined were 802.11a/g, designed for 5 GHz and 2.4 GHz band respectively. Recent standards, 802.11n and 802.11ac, provides higher bitrates by using MIMO and more bandwidth. However, a high bitrate is not a sufficient condition to applications where short packets are transmitted, as maximum packet rate is similar to all the cited PHYs.

If no MIMO is used, the most efficient OFDM-based PHY for transmitting short packets is 802.11g [18]. Therefore 802.11 OFDM PHYs inefficiencies with short packets are addressed using 802.11g as example.

The frame structure of an 802.11g frame transmitted using a BW of 20 MHz is shown in Fig. 4.

Each field of 802.11g frame is briefly described below:

- *Short Training Field (STF):* it is used for Automatic Gain Control (AGC), energy detection and frequency correction. Its length is 8 µs.
- *Long Training Field (LTF):* it is used for channel estimation and fine frequency offset estimation. It has two Long Training Symbols (LTS), each of which lasts 4 µs.
- *SIGNAL symbol:* each 802.11g frame contains a configuration symbol, which carries the frame length and modulation coding scheme (MCS) information. Its length is 4 µs.
- Payload: this field contains the data from higher layers. Its length is a multiple of 4 µs (1 OFDM symbol duration, T_{OFDMS}) and it depends on the number of bytes in the payload and the MCS used in the transmission. Last OFDM symbol must be filled with pseudo-random data until the symbol is complete.

Packet transmission duration can be hence computed as a function of the preamble length, the number of bytes in the payload and the MCS used in the transmission:

$$t_{frame} = T_P + T_{SIGNAL} + \left\lceil \frac{N_b + N_{SB} + N_{PB}}{N_{DBPS}} \right\rceil \cdot T_{OFDMS}, \quad (1)$$

where T_P is the preamble duration, T_{SIGNAL} is the SIGNAL symbol duration and T_{OFDMS} is an OFDM symbol duration. Furthermore, N_b is the number of bits in the payload and N_{DBPS} is the number of bits in an OFDM symbol and takes values from 24 to 216. 22 bits are added, 16 bits before the payload (N_{SB}) and 6 bits after the payload (N_{PB}). Finally, $\lceil\cdot\rceil$ is the operator ceil, which rounds up the value to the smallest integer value greater than or equal to its arguments value.

Fig. 4. 802.11a/g Frame Format.

Two main inefficiencies in short packet transmission can be derived from the previous description and equation (1):

- *Preamble length:* the number of payload symbols is small in short packets, thus the time consumed to transmit the whole packet is high compared to the time consumed to transmit the information.
- *Padding zeros in last OFDM symbol:* last OFDM symbol must be filled with pseudo-random data to ensure the number of bits in the transmission is multiple of the OFDM symbol size. When the number of payload symbols is low, the amount of pseudo-random data in the last OFDM symbol may significantly reduce airtime efficiency.

As an example, a packet with a payload of 10 bytes and MCS = 2 (QPSK and ½ convolutional code), being $S_{bits} = 48\ bits$ consumes 6.7 µs to transmit its payload, while the time consumed to transmit the whole packet is 32 µs. This leads to an airtime efficiency of 21%.

In order to reduce the airtime consumed to transmit short packets and increase packet rate, we have defined two waveforms designed for DL and UL frames respectively. This dual waveform exploits the asymmetries between downlink channel and uplink channel, the periodicity of the RT traffic and the slow variation of the communications channel. Wireless SHARP coding/decoding scheme is the same used in 802.11g, so the PHY implements the same MCS coding and follows the same numbering [13], that is: BPSK for MCS 0/1, QPSK for MCS 2/3, 16-QAM for MCS 4/5 and 64-QAM for MCS6/7.

2) DL Waveform: long preamble waveform with PHY frame aggregation

In a standard 802.11 network, each DL frame contains a single DL packet which is transmitted separately with its own preamble and signal symbol. As stated before, this transmission is very inefficient when the application transmits very short packets. Thus, we propose using PHY frame aggregation in the DL Waveform to greatly increase transmission efficiency. This technique is shown in Fig. 5 and described below.

As the SHARP AP may send several DL packets in a row during DL period, an efficient way to transmit those packets is generate a frame joining together one preamble, one SIGNAL symbol and all the OFDM symbols generated in the modulation process of each payload with their own MCS.

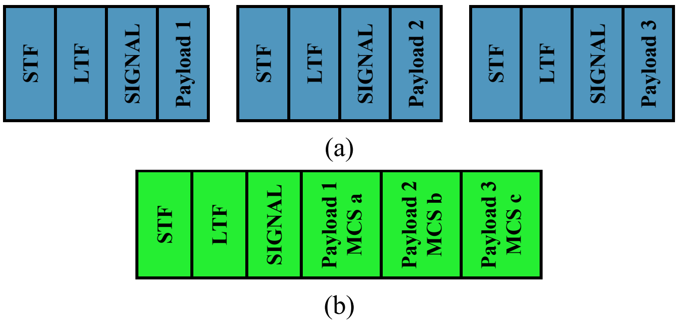

Fig. 5. Comparison between 802.11g (a) and SHARP DL PHY.

The use of 802.11g preamble ensures frame detection, frequency and AGC correction and channel estimation at slave nodes receivers. Furthermore, as the payloads are independent and each slave node knows their payload position, MCS and length, slave nodes only need to demodulate their assigned OFDM symbols. Finally, the SIGNAL symbol included after the frame preamble is used as a mechanism to block standard nodes in receiver mode, as explained in Section II.*D.* The SIGNAL symbol is ignored by slave nodes, as it does not carry any useful information.

This proposal has several advantages with regard to the 802.11 standard for industrial applications and few disadvantages, if any. Firstly, it vastly reduces airtime when transmitting short packets compared to 802.11g legacy transmission as the transmission only requires one preamble and one Interframe Space. Furthermore, PHY frame aggregation provides more flexibility than other forms of aggregation (e.g. MAC aggregation), as the OFDM symbols of each RT packet may use different MCS. Finally, the implementation of this waveform requires little changes in standard hardware as it is based on the standard modulation/demodulation scheme.

3) UL Waveform: short preamble waveform

A long preamble is efficient at DL, due to the DL waveform proposed is based on frame aggregation. However, UL frames cannot be grouped, as frames are sent from different nodes to the AP. Therefore, we have considered using a short preamble waveform to increase the efficiency of short packets, similar to the proposal done in [19].

SHARP AP does not know channel information (attenuation, frequency offset), but slave nodes do, due to the detection and demodulation of the DL frame during the DL period.

If frequency correction and gain adjustment are performed at the slave node transmitter, the AP only needs to keep a fixed gain and a frequency offset value equal to 0 to detect and demodulate UL frames. This procedure is used in mobile communication standards, such as LTE [20]. However, this mechanism can only be used if the channel remains invariant during all the communication cycle. The measurements presented in [2] show that the variation of the channel attenuation over time in an industrial environment is slower (10 - 30 ms) than t_{cycle} (0.5 – 2 ms), so this consideration can be done. To mathematically describe this channel variation, we have defined the channel attenuation coherence time (t_{ch}), which is the time duration over which two samples of the channel attenuation variable can be considered uncorrelated. This parameter is related to the channel coherence time, but defined in terms of attenuation instead of channel impulse response.

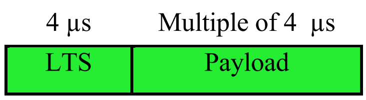

Fig. 6. SHARP UL Waveform frame format.

Under the assumption of a $t_{ch} >> t_{cycle,}$ the preamble can be shortened, as the SHARP AP can easily detect UL frames with only one LTS symbol. The format of UL frames is shown in Fig. 6. Fine channel estimation process must be still done at the receiver to obtain fine frequency correction, constellation rotation and equalize OFDM subcarriers.

D. Mechanism to ensure backward compatibility with 802.11 standard

To ensure backward compatibility with 802.11 standard, five mechanisms are used, which are described below:

1) Virtual Carrier Sense through CTS-to-self

A CTS-to-self frame is sent by the AP with MCS = 0 and a duration value equal to the duration of the RT period. This frame indicates the channel will be busy for a time equal to the duration of the RT period. Every legacy node that has received the CTS must set their NAV [13] to the value specified in the duration field of the CTS frame.

The NAV is a falling counter used to virtually know if the channel is idle or busy. If its value is higher than 0 µs, the channel is busy, so the station cannot transmit. When its value reaches 0 µs, the channel is supposed to be idle, so the station may gain access to the medium through the CSMA/CA scheme.

2) PHY Carrier sense during RT period

PHY Carrier sense is a mechanism of 802.11 to decide whether the channel is busy or idle by continuously reading the energy in the RF channel. As the RT period is fully occupied by wireless transmissions, the channel appears to be busy during the duration of the RT period for 802.11 stations, thus they cannot gain access to the medium.

3) SIGNAL symbol in long preamble Waveform

Every DL frame contains a SIGNAL symbol, which is used to block 802.11 nodes in the demodulation process until the end of the RT period. The SIGNAL symbol MCS and length values are such that the 802.11 nodes will detect the DL frame airtime duration is equal to the RT period. This erroneous frame will be discarded, thanks to the Cyclic Redundancy Check (FCS field [13]).

4) Controlled Phase (CP) before RT period

In the controlled phase, the SHARP AP must take the control of the channel through transmitting legacy frames, denying the access to the wireless medium to the 802.11 nodes. If the controlled phase starts and there is a current transmission, the AP must wait for the ending of the frame to take the control of the channel. Otherwise, the SHARP AP directly takes the channel at the start of the CP. CP duration must be high enough to ensure no legacy frame occupies the RT period:

$$t_{CP} = t_{frame} + t_{ACK} + 2 \cdot t_{SIFS,sta}, \quad (2)$$

where a Short IFS (SIFS) duration is equal to 16 µs according to the standard.

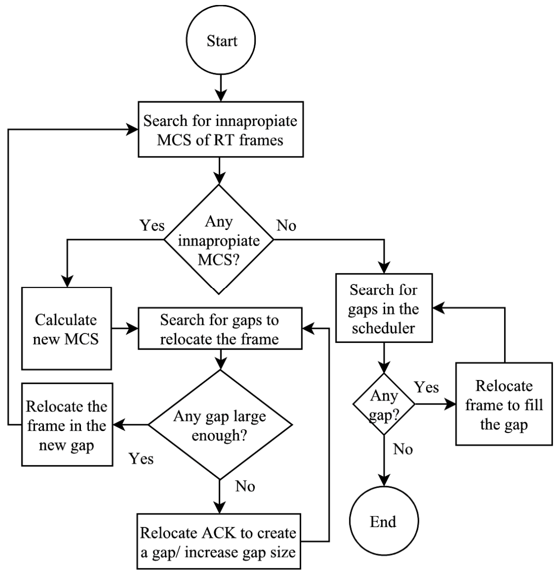

Fig. 7. Rescheduling flowchart.

5) Maximum size of legacy frames

Maximum legacy frame size must be small to obtain a small CP size. We use two mechanisms to force legacy nodes to send small frames:

- *802.11 basic rate configuration:* APs can force the nodes to use a minimum MCS (e.g. MCS = 2) to improve the network mean bitrate. We use this configuration to reduce the maximum frame length.
- *MTU size at link layer:* MTU size defines the maximum packet length in bytes that can be encapsulated into MAC frames. The MTU size configuration must be done manually in every legacy node. However, legacy nodes connected to the wireless network should be included in the network planning, so their pre-configuration is compulsory.

E. Rescheduling process

In the rescheduling process the MCS of the RT frames is adjusted to ensure a low mean PER. The rescheduling algorithm decides whether the MCS of the RT frames must be adjusted. The algorithm may be different for each application so it is not included in the system specification. However, an outlining of a possible rescheduling process is described in this subsection.

We have considered three restrictions: i) there cannot be any overlapped slots in the scheduler at any time to avoid interferences, ii) one rescheduling packet can only contain rescheduling information for one frame from the UL period and one element from the DL period (either DL payload or ACK) and iii) the rescheduling is used when the mean channel attenuation varies drastically. Although these restrictions reduce rescheduling speed, it is simpler, easier to implement, and more predictable.

Regarding to the variables used by the rescheduling algorithm, we have only contemplated mean Received Signal Strength Indicator (RSSI), but other metrics, such as Packet Error Rate (PER) or channel statistics, might be useful.

An example of a possible algorithm to reduce the MCS of a frame at the DL period is explained below and shown in Fig. 7:

- The AP detects that the MCS of a frame is too high to ensure a low PER.
- The AP calculates a new MCS and searches a slot to relocate the frame. The slot must be as close as possible to the start of the DL period and before the ACK slots.
- If there is no gap between the DL frame and the ACK slots, it must relocate ACKs to create a gap large enough to relocate the frame.
- The relocation information is sent to the corresponding slave nodes and it is retransmitted until the AP receives the ACK response.
- After relocating, the AP must refill the gap left in the old frame position. The AP relocates the frames, one by one, filling the gaps until the gap position is after the ACK slots, hence eliminating the gap in the DL period.

The process at the UL channel is identical, unless there is no ACK relocating. The rescheduling process has not been included in section III and IV, as the simulations are focused on the system reliability.

III. SIMULATION SETUP

To evaluate Wireless SHARP performance, we have implemented both MAC and PHY layers over OMNeT++ 5.0 simulator. PHY layer implementation includes the MCS and length of each RT frame, and the calculation of the RT frames airtime. On the other hand, the MAC scheme includes every MAC feature, excluding frames at CC, as they do not influence the system performance.

The simulations have been carried out over two industrial channel models both with Non-Line-Of-Sight (NLOS) conditions and Rayleigh fading (CM8 and Scenario 7 [21], noted in this article as channel 1 and channel 2 respectively). Channel 1 has an rms delay spread of 89 ns while channel 2 has an rms delay spread of 29 ns. The channel models have been generated using the Communications System Toolbox™ provided by Matlab.

As shown in [21], channel conditions may be very different from one scenario to other, thus each case must be precisely studied to ensure a proper operation of the system. This may be done at network initialization, as the AP can measure the channel variation and behavior.

We found in preliminary simulations that the main source of packet errors using 802.11g is the channel fading due to its time varying behavior, while the effect of frequency selectivity is low due to OFDM robustness in dispersive channels. In order to obtain realistic and accurate results, we have estimated the fading distributions for both channels in Matlab, and then included the distributions and their temporal behavior (t_{ch}) in OMNeT.

We have evaluated the proposed PHY performance in Matlab. The proposed PHY and 802.11g PHY performance should be similar, as both PHYs use the same coder/decoder. Therefore, the evaluation of the wireless SHARP PHY has been carried out with the 802.11g modem included in the WLAN System Toolbox™ provided by Matlab. This evaluation includes frequency selectivity effects due to multipath dispersion, but it does not include Rx power fading, as it is already implemented in OMNeT. Therefore, we have calculated 802.11g PER as a function of the instantaneous Rx power. To do so, the next algorithm has been used:

TABLE I. INTERFRAME SPACE (IFS) BETWEEN FRAMES

Actual frame	Next frame	Equivalent 802.11 IFS	Interframe space (µs)
CTS	DL	SIFS	10
DL	ACK	SIFS	10
ACK	ACK	RIFS	2
ACK	RTx DL	SIFS	10
UL	UL	RIFS	2
UL	RTx UL	SIFS	10
RTx UL	UL	SIFS	10

- For each mean Rx power bin [from -90 dBm to -60 dBm].
- For each realization.
- Take a realization of the impulse response of the channel model.
- Obtain the instantaneous Rx power of the channel realization.
- Reclassify the simulation to its correspondent instantaneous Rx power bin.
- Send a packet and evaluate if it is correctly demodulated.

Moreover, we have also calculated the mean MAC to MAC delay, and maximum and minimum delay bounds of RT frames. Maximum delay bound (t_{max}) has been calculated as the end of the RTx DL/UL period (t_{eRTx}) minus the start of the DL/UL period(t_{sP}) (eq. (3)), while minimum delay bound (t_{min}) has been calculated as the time used to transmit the payload (t_{Tx}) plus PHY and MAC processing time, equivalent to a Wireless SHARP SIFS, $t_{SIFS,WSHARP}$ = 10 µs, eq. (4).

$$t_{max} = t_{eRTx} - t_{sP}. \quad (3)$$

$$t_{min} = t_{Tx} + t_{SIFS,WSHARP}. \quad (4)$$

A. Simulation parameters

1) IFS

IFS is the guard time between frames that is used to allow the transceiver to finish the demodulation of the actual frame and prepare it to demodulate the next frame or generate a response to a frame (e.g. an ACK response in 802.11). The minimum IFS needed depends on the design of the PHY layer and the modem speed. For this set of simulations, IFS are selected using 802.11g IFS [13] as reference and their values are shown in Table I. IFS values are slightly lower than 802.11 IFS due to our system does not need to demodulate the SIGNAL symbol.

2) Control Packets Sizes

The size and MCS of control packets should be fixed and known by every node in the network. Table II resumes their MCS, estimated sizes, and consumed airtime.

TABLE II. CONTROL PACKET SIZES

Packet Type	Payload (bytes)	Waveform	MCS	Airtime (µs)
CTS	14	Standard	0	44
RT-Beacon	11	Long (aggregated in DL frame)	0	20 (preamble not included)
ACK	6	Short	0	16
RTx DL request	11	Long	0	40 (preamble included)
RTx UL request	9	Long (equivalent to standard)	0	36 (preamble included)

B. Scenario for the evaluation of RT performance

The presented scenario is used to show the throughput and reliability bounds of the proposed technology and does not represent a real industrial environment, where the sensors and actuators of the network have heterogeneous characteristics (Tx power, payload length, node radio channel, sampling rate, etc.). Nevertheless, this scenario would be similar to a Factory Automation scenario with several sensors and actuators measuring small sets of data (position, speed, acceleration, event triggering, etc.).

Table III summarizes the specific parameters for the simulated scenarios. The amount of nodes is different for each MCS and has been chosen to obtain a similar RTx period duration in every simulation. As it can be seen, the number of nodes supported by a Wireless SHARP network is considerable higher than other proposals based on 802.11g standard, such as IsoMAC [10] or [11], that could only support up to four nodes with the same control cycle.

TABLE III. SIMULATION PARAMETERS

MCS	Parameter		Value	Unit
All MCS	t_{cycle}		1	ms
	Rx noise threshold		-90	dBm
	t_{ch}		30	ms
	Tx power		10	dBm
	RT frames length (included MAC)		11	Bytes
	Sensors and actuators sampling rate		1	kHz
	Nodes Data rate		32 (4 bytes/ sample)	kbps
	Fading model		Rayleigh NLOS (Both channels)	
MCS 0	Number of nodes	DL	11	
		UL	11	
	Rtx duration	DL	133	µs
		UL	171	µs
	Rtx MCS		0	
MCS 2	Number of nodes	DL	15	
		UL	15	
	Rtx duration	DL	154	µs
		UL	174	µs
	Rtx MCS		0	
MCS 4	Number of nodes	DL	20	
		UL	20	
	Rtx duration	DL	137	µs
		UL	161	µs
	Rtx MCS		2	

C. Scenario for the evaluation of Best Effort performance

We have also simulated maximum achievable traffic rate in the Best Effort period. This scenario has three elements: one SHARP AP that transmits CTS frames and takes the control of the channel in the CP through sending CTS frames and two legacy nodes transmitting at the maximum capacity allowed by 802.11 mechanisms. CP size has been set to 136 µs according to Eq. (2) using MCS = 2 and a frame size of 74 bytes ($t_{ACK} = 32\ \mu s$ and $t_{frame} = 72\ \mu s$). Traffic rate has been evaluated over three MCS (2, 4 and 7) and different Best Effort durations. We have considered for this scenario that there are not erroneous frames due to radio propagation, but there may be frame collisions.

IV. RESULTS

We have evaluated the performance of the system for DL and UL periods in terms of raw PER (without retransmissions), and PLR, which includes the retransmission scheme, for both channel 1 and channel 2. PER and PLR results under channel 1 are represented in Fig. 8, while Fig. 9 contains PER and PLR curves obtained under channel 2. DL and UL results are represented by the same curve, as they are nearly identical.

Regarding the results obtained under channel 1, PER results are as expected, the lower the MCS the better the reliability. We have found the system can achieve a PER of 10^{-8} under a mean Rx power of -68 dBm without retransmissions using MCS 0. However, MCS 0 provides very low bitrate.

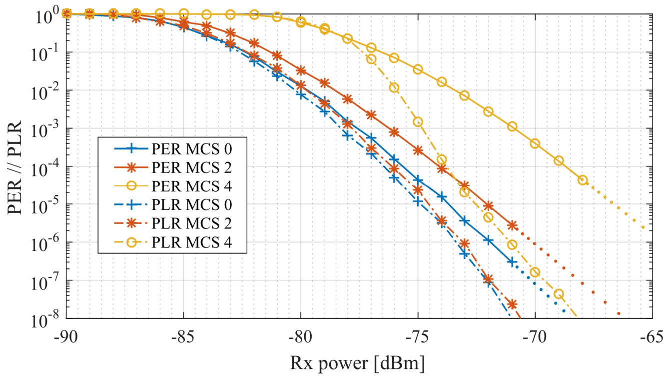

Fig. 8. PER and PLR results under channel 1.

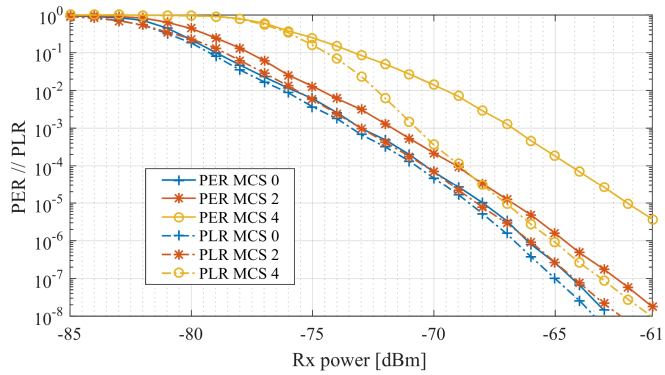

Fig. 9. PER and PLR results under channel 2.

TABLE IV. GAIN BETWEEN MODULATION SCHEMES UNDER CHANNEL 1

	Gain MCS 0 – MCS2 (dB)	Gain MCS 2 - MCS 4 (dB)
PER	2	6
PLR	~0	3

TABLE V. MAXIMUM, MINIMUM AND MEAN MAC TO MAC PACKET DELAY UNDER CHANNEL 1

Channel	UL	UL	UL	DL	DL	DL
MCS	0	2	4	0	2	4
Max Delay (μs)	426	394	371	497	526	549
Min Delay (μs)	26	22	18	26	22	18
Mean delay for Rx power = -74 dBm (μs)	26.002	22.017	21.060	26.003	22.026	22.84
Mean delay for Rx power = -71 dBm (μs)	26.000	22.001	18.15	26.000	22.001	18.24

Focusing on PLR results, the proposed retransmission scheme seems to obtain little improvements in MCS 2 and MCS 0 results (1-2 dB), unlike MCS 4 PLR, which has a gain of 5 - 6 dB with regard to MCS 4 PER. As shown in Table IV the gain between MCS 4 and MCS 0/2 is as low as 3 dB. Therefore, the use of MCS 4 as the basic transmission rate is almost compulsory, as it provides 33.3% more packet rate than MCS 2 and nearly doubles MCS 0 packet rate with very little differences in reliability.

A change of slope in the PLR MCS 4 curve can be clearly observed at -74 dBm (Fig. 8) At this point the retransmission scheme collapses as the number of retransmissions exceeds the Rtx period capacity, so the PLR greatly increases its value.

On the other hand, PER/PLR curves obtained under channel 2 (Fig. 9) have a similar behavior but with a 7 dB shift to the left with respect to channel 1 curves. As can be seen, the system reliability is considerably lower when the channel has a low delay spread and Rayleigh fading. This is mainly due to the fading probability of channel 2 is higher than the fading probability of channel 1. As stated before, the performance of the system clearly depends on the quality of the channel, and it must be taken into account when the network is designed.

summarizes MAC to MAC delay results. Maximum delay bound is less than 550 μs in every scenario, as the retransmissions are always carried out inside the same communication cycle. Furthermore, the mean delay is very close to the minimum delay when the number of retransmissions is low (PER<10^{-3}).

With regard to Best Effort traffic, we have found that the Best Effort duration must be higher than 200 μs to ensure legacy stations can gain access to the wireless media (Table VI), due to legacy stations must listen the radio channel during a minimum time of 28 μs plus a random backoff time [13] to gain access to the channel.

Furthermore, when the duration of the Best Effort is equal or smaller than 300 μs, the maximum number of legacy frames transmitted during a SuperFrame is one frame plus an ACK, so maximum achievable data rate is the same for all MCS. In a typical industrial scenario, the Best Effort period may be smaller than 300 μs, as the RT transmissions should occupy most of the wireless medium. In this case, the system may be configured to use only MCS = 2 during the Best Effort period.

TABLE VI. MAXIMUM ACHIEVABLE BEST EFFORT TRAFFIC RATE

MCS \ BE (μs)	600	500	400	300	250	200	150
2	1.08	0.916	0.624	0.488	0.395	0.192	0
4	1.22	1.01	0.702	0.501	0.394	0.189	0
7	1.30	1.07	0.80	0.498	0.405	0.195	0

Traffic rate is in Mbps*

Finally, although Best Effort maximum traffic rate is quite low, this period ensures the RT elements can be accessed and easily configured through standard mechanisms and hardware, such a computer or a server. Finally, maximum the Best Effort traffic rate is enough for lightweight applications, such as transferring small files, web-based/App-based remote control interfaces, Over-The-Air updates, monitoring, etc.

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

In this paper a novel hybrid architecture with the aim of increasing the performance, flexibility and reliability of nowadays wireless solutions for industrial control applications is outlined. The paper is focused on the wireless segment, which includes novel PHY and MAC layers, offers high reliability as well as high packet rate with short packet transmission. Its main features are: 802.11 backward compatibility, RT traffic support and a communication cycle as low as 1 ms.

Regarding PHY layer, we have proposed a modification of 802.11g PHY to greatly increase packet rate when transmitting short packets. This modification is based on the aggregation at PHY level of DL traffic and the reduction of the preamble size of the UL traffic. In order to support RT traffic, a TDMA-based MAC with a semi-persistent scheduler and a dynamic retransmission scheme has been proposed.

The performance of the system has been evaluated through OMNeT simulations in terms of PER and PLR. To the best of our knowledge, the system outperforms other state-of-the-art wireless RT proposals for industrial applications based on WLAN, as the number of nodes supported by the system is higher and the reliability is better for the same SNR. Finally, regarding Best Effort period, we have found that the maximum achievable traffic rate is low but enough for lightweight applications (e.g. configuration files, logs, web interface, etc.).

B. Future work

Several aspects of the wireless technology will be addressed in future reviews to increase Wireless SHARP performance and reliability.

Firstly, we have found that the fading due to the channel paths variation is the main source of errors in the communication. As the coherence time is much higher than the duration of a communication cycle, one large fade in the channel between the AP and a slave node could interrupt their communication during one or more cycles. This fading probability can be reduced by adding some redundancy to the system, which may be implemented with spatial diversity or frequency redundancy.

Secondly, the PHY layer has not been optimized. Adjusting OFDM symbol length, Cyclic Prefix, modulation scheme, etc. would lead to an improvement in reliability and efficiency.

Thirdly, MAC headers must be defined carefully in order to reduce the inefficiencies due to packet overhead sending only essential information.

Fourthly, an appropriate scheduling policy is essential to ensure a low packet error rate, and its operation depends on the particular application (QoS, scenario, number of nodes, packet size, channel, etc.). Therefore, some theoretical studies may be carried out to obtain the system performance and reliability bounds subject to the network configuration parameters and scenario, thus obtaining the optimum scheduling policy without the need of performing simulations with a high computational complexity for every use case.

The design of SHARP architecture, including both wired and wireless segment, will be addressed in future works. These articles will be focused on three main aspects: the integration of the wireless and wired segment, the AP functionality as a bridge between both segments and the packet transmission flow from the wired to the wireless segment and vice versa.

The proposed wireless architecture has been simulated in a factory automation scenario. In future works we will adapt wireless SHARP to other URLLC scenarios, such as automotive or railway.

Finally, the implementation of SHARP is a big challenge as it is not based on standard PHY and MAC layers. We are currently working on an implementation of Wireless SHARP on a Zynq (FPGA + ARM SoC) to test its performance and suitability for industrial communications over real conditions.

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