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Physical Layer Design of High Performance Wireless Transmission for Critical Control Applications

Michele Luvisotto, *Student Member, IEEE,* Zhibo Pang, *Senior Member, IEEE,* Dacfey Dzung, *Member, IEEE,* Ming Zhan, *Member, IEEE* and Xiaolin Jiang, *Student Member, IEEE*

***Abstract*—The next generations of industrial control systems will require high–performance wireless networks (named WirelessHP) able to provide extremely low latency, ultra–high reliability and high data rates. The current strategy towards the realization of industrial wireless networks relies on adopting the bottom layers of general purpose wireless standards and customizing only the upper layers. In this paper, a new bottom–up approach is proposed through the realization of a WirelessHP physical layer specifically targeted at reducing the communication latency through the minimization of packet transmission time. Theoretical analysis shows that the proposed design allows a substantial reduction in packet transmission time, down to 1 µs, with respect to the general purpose IEEE 802.11 physical layer. The design is validated by an experimental demonstrator, which shows that reliable communications up to 20 meters range can be established with the proposed physical layer.**

I. Introduction

In the last years, Industry 4.0 has emerged as the dominant paradigm for the next generation of industrial systems [1]. The realization of this vision requires, among several other aspects, the introduction of high–performance wireless communication networks explicitly designed for industrial control applications, that we generally label as WirelessHP (High Performance) [2]. The field of application of such networks ranges from building and process automation [3] to the more critical scenarios found in factory automation [4], power systems automation [5] and power electronics control [6]. Wireless networks to be deployed in industrial control applications need to satisfy a set of requirements which is significantly different from that generally associated with home/office wireless networks. These requirements include deterministic communication, extremely low latency (below 1 µs), extremely high reliability and high data rates (above 1 Gbps) [2]. Other specific aspects of WirelessHP include short packets (payloads of 100 bits or lower) [7], predictable traffic patterns, fixed number of nodes, low mobility, short range (up to some meters) and centralized network control and management. For a detailed explanation of the requirements, challenges and directions that characterize the WirelessHP scenario, please refer to [2].

M. Luvisotto is with the Department of Information Engineering, University of Padova, Via Gradenigo 6/B, 35131, Padova, Italy, e-mail: michele.luvisotto@dei.unipd.it.

Z. Pang is with ABB Corporate Research, Forskargränd 7,SE-721 78 Västerås, Sweden (e-mail: pang.zhibo@se.abb.com).

D. Dzung is with ABB Corporate Research, 5405 Baden-Dättwil, Switzerland (e-mail: dacfey.dzung@se.abb.com).

M. Zhan is with the College of Electronics and Information Engineering, Southwest University, Chongqing 400715, P.R. China (e-mail: zmdjs@swu.edu.cn).

X. Jiang is with the Department of Network and Systems, Royal Institute of Technology (KTH), Osquldas Väg 10, SE-100 44, Stockholm, Sweden (e-mail: xiaolinj@kth.se).

The introduction of wireless communications in industrial networks has long been an important research topic [7]. The common approach so far is based on customizing the upper layers of general purpose wireless standards to achieve deterministic communications, while keeping the bottom layers (physical and sometimes data–link) untouched. This strategy led to the development of industrial wireless sensor networks for building and process automation, such as those described by the standards WirelessHART [8], ISA100.11a [9] and WIA-PA [10], as well as that proposed in [11], which are all based on the IEEE 802.15.4 bottom layers. Other solutions, such as WISA [12], that will be standardized as PNO WSAN [13], are instead based on the IEEE 802.15.1 standard. Furthermore, since the data rate offered by the IEEE 802.15 family of standards is typically limited, more recent works have considered the IEEE 802.11 standard for Wireless Local Area Networks (WLANs) [14] as a foundation for industrial wireless networks, such as the WIA-FA standard [15] and the RT-WiFi protocol proposed in [16]. Finally, the use of new generation cellular networks, such as Long Term Evolution (LTE) and the upcoming 5G has recently been suggested [17].

While keeping the bottom layers of general purpose wireless standards can allow faster standardization and easier intercompatibility, it represents a fundamental bottleneck to network performance. As an example, if the IEEE 802.11 physical (PHY) layer is employed, the transmission time for a packet arbitrarily short can not be lower than roughly 2 µs, even when the latest version of the standard (IEEE 802.11ad in the 60 GHz band with multi–Gbps data rate) is employed [2]. Similarly, even though 5G promises low–latency communications, the expected end–to–end latency will be no lower than 1 ms, due to the network overhead incurred in the underlying cellular infrastructure (there is also some doubt that industrial plant operators are willing to rely on external cellular telecommunications providers for their real–time on–site control applications).

The motivation for this paper, hence, lies in the significant gap between the performance of industrial wireless solutions

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currently found in both literature and marketplace and the requirements of the most critical deployment scenarios, which demand latency at the microsecond level or even lower, together with optical fiber–level reliability and multi–Gbps data rates. The approach envisioned by WirelessHP [2], therefore, totally differs from the common strategy followed in the design of industrial wireless networks, in the sense that it proposes a completely customized protocol stack, where each layer is optimized towards the specific requirements of industrial control applications, rather than attempting to satisfy all generic requirements of cellular/5G systems. Within this framework, the most important contribution of this paper is a proposal for a WirelessHP PHY layer design specifically targeted at ultra–low latency, as it represents the most difficult challenge.

The proposed PHY design, based on Orthogonal Frequency Division Multiplexing (OFDM), aims at reducing the inefficiencies that affect short packet transmission in other wireless systems, such as IEEE 802.11. To this purpose, the length of the PHY layer preamble is reduced (while still ensuring reliable packet decoding) and the OFDM parameters are optimized towards the decrease of packet transmission time. Theoretical analyses show that the proposed design is able to approach the highly demanding latency requirements of critical industrial control applications (provided that enough bandwidth is available) and that it significantly outperforms the physical layer of the IEEE 802.11 standard. As a further important contribution, an experimental narrowband demonstrator based on a Software–Defined Radio (SDR) platform has been developed to validate the presented WirelessHP PHY. The setup serves as a proof–of–concept rather than as a complete implementation, as it is limited to a 5 MHz bandwidth. However, it proves that the packet transmission time expected via theoretical analysis for this bandwidth (roughly 20 µs) can be achieved and that reliable communication is established at more than 20 meters range. Further work is planned on improvements of the demonstrator, of specific aspects of the PHY design, such as synchronization, channel coding, spatial diversity, beamforming, etc., as well as on the design of upper layers to achieve determinism and high reliability.

The rest of this paper is organized as follows. Section II introduces the problem of achieving low–latency communications with short packets in an industrial network and argues that packet transmission time represents the ultimate bottleneck. Section III describes the IEEE 802.11 OFDM PHY and computes the packet transmission time in different versions of this standard. Section IV presents the WirelessHP low–latency PHY design and compares its performance with those of IEEE 802.11 via theoretical analysis. The validation through the narrowband SDR demonstrator is described in Section V. Finally, Section VI concludes the paper, discusses some possible limitations of the proposed approach and outlines the future directions of research.

II. Low–latency communications in industrial networks

In the last years, short–packet wireless communication has gained a lot of interest among the scientific community, mainly driven by the development of the fifth generation of cellular

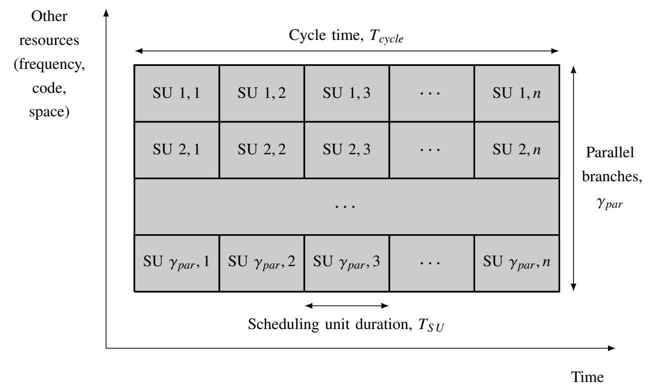

Fig. 1. Cyclic communication schedule over parallel branches.

standards (5G), which, among many other use cases, targets also machine–to–machine (M2M) communications with ultra–low latency, ultra–high reliability and short packet size [18]. However, the latency targets in 5G are still much higher than the requirements for the most demanding industrial communication applications: the former scenario requires end–to–end latency around 1 ms, while the latter demands latency in the µs scale. On the other hand, many assumptions typical of industrial wireless can be exploited to achieve the required timeliness, such as the fact that communications are generally tightly scheduled and follow a cyclic pattern.

In an industrial setup, a meaningful indicator of the latency level is the update rate, namely how often a single node in the network is able to transmit and/or receive an updated message. If communications are organized in a cyclic fashion, the update rate can be expressed as the inverse of the cycle time. The most advanced industrial control applications require update rates as high as 100 kHz and, hence, cycle times as low as 10 µs [2].

In the following, we assume a star communication topology with one controller at the center and N nodes. Fig. 1 shows the generic communication schedule for this case, which is cyclically repeated over time and uses γ_{par} independent parallel branches in frequency, spreading code and/or space (Multiple–Input Multiple–Output, MIMO). The basic block of the schedule is called scheduling unit (SU) and it is assigned to a single link between controller and node, in the uplink or downlink direction. Each link–direction pair is mapped to k_{red} different SUs, in order to achieve a certain redundancy level able to guarantee the required application layer reliability.

In a network of N nodes, assuming that each link is active in both directions, the cycle time is hence given by

$$T_{cycle} = \frac{k_{red} \cdot 2N \cdot T_{SU}}{\gamma_{par}} \quad (1)$$

where T_{SU} is the duration of a scheduling unit. While the parameters N, k_{red} and γ_{par} depend on the application requirements, upper layers design and available resources, the SU duration only depends on PHY layer design. The focus of this work, hence, will be on reducing T_{SU} as much as possible, in order to allow very high update rates. Specifically, the target for advanced control applications is to have a SU as short as 200 ns [2]. While some guard margins should be reserved for

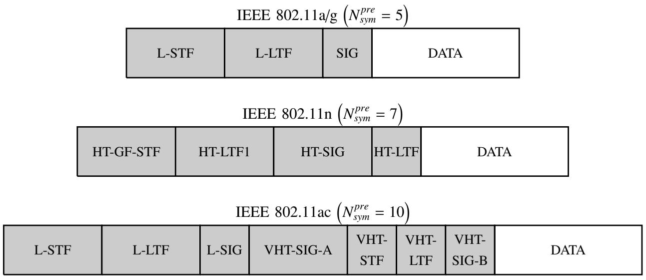

Fig. 2. PPDU format in different versions of the IEEE 802.11 standard. Preamble symbols are in light gray, while data symbols are in white. For IEEE 802.11n/ac the number of spatial streams is set to 1 and, for IEEE 802.11n, the Greenfield preamble is considered [14].

synchronization, propagation and elaborations, the majority of time during a SU is devoted to packet transmission. For this reason, in this paper the goal will be to achieve the shortest possible transmission time for small packets, with payloads of 100 bits or lower. The value of 100 bits is considered indicative for the targeted applications, and includes bits reserved for destination and source addresses, status and command data, and error checking.

III. Packet transmission time in IEEE 802.11 OFDM

Most versions of the IEEE 802.11 standard use OFDM at the PHY layer, from the legacy IEEE 802.11a and g to the more recent IEEE 802.11n and ac.

In an OFDM–based PHY, the transmitted waveforms are grouped in OFDM symbols. Within each symbol, information bits are mapped onto N_{FFT} subcarriers in frequency domain, which correspond to N_{FFT} samples in time domain via the Fast Fourier Transform (FFT). The last N_{cp} time–domain samples are repeated and appended at the beginning of the symbol, forming the cyclic prefix (CP), that allows to avoid inter–symbol interference (ISI) in multipath fading channels. The transmission time of an OFDM symbol is hence given by

$$T_{sym} = T_s \cdot \left(N_{cp} + N_{FFT}\right) \tag{2}$$

where T_s is the sample time. The occupied bandwidth B is generally equal to the sample frequency $F_s = 1/T_s$, while the subcarrier spacing, i.e., the bandwidth assigned to a single subcarrier, is given by $\Delta_{SC} = B/N_{FFT}$.

A PHY layer Packet Data Unit (PPDU) is formed by a certain number of OFDM symbols, the first ones used for the preamble and the last ones for the data.[1] The number of symbols destined to the PHY layer preamble, N_{sym}^{pre} varies among the different versions of the IEEE 802.11 standard, as reported in Fig. 2. The number of symbols used for data, N_{sym}^{data}, instead, depends on the amount of data to send L (in bits), the number of subcarriers used for data N_{dsc}, the modulation order M, the channel coding rate R_c and the number of spatial streams N_{ss}, according to

$$N_{sym}^{data} = \left\lceil \frac{L}{N_{dsc} \cdot \log_2 M \cdot R_c \cdot N_{ss}} \right\rceil \tag{3}$$

[1]The “data” part includes the payload as well as all the headers and trailers added by upper layers (i.e., is the PHY layer Service Data Unit, PSDU).

The overall packet transmission time can hence be computed as the total number of OFDM symbols times the symbol duration, which, taking Eq. (2) into account, yields[2]

$$T_{pkt} = T_s \cdot \left(N_{cp} + N_{FFT}\right) \cdot \left(N_{sym}^{pre} + N_{sym}^{data}\right) \tag{4}$$

Tab. I reports the packet transmission time when L = 100 bits, no channel coding is employed ($R_c = 1$) and only 1 spatial stream is used, for different versions and configurations of the IEEE 802.11 standard and for low–order modulations. We assume that only the PHY layer of IEEE 802.11 is employed while the upper layers are customized in order to compress headers and trailers (IEEE 802.11 data–link header is 28 Bytes long [14], hence the PSDU length L would be much higher than 100 bits).

It can be observed from the table that there is a large gap between the IEEE 802.11 transmission time of short packets and the requirements of low–latency industrial control applications (200 ns), confirming the fact that current wireless standards can not provide satisfactory performance [2]. Moreover, it can be noticed that the most recent standards, such as IEEE 802.11n and ac, although employing much higher bandwidth up to 160 MHz, show a slightly increased packet transmission time with respect to the old IEEE 802.11a/g. New standards, indeed, are not optimized at all for small packet transmissions, due to both their high number of preamble symbols, as reported in Fig. 2, and their high FFT size, which is suboptimal when only few bits have to be transmitted. In the rest of this paper an optimized PHY design able to efficiently exploit the available bandwidth will be presented.

All the versions of the IEEE 802.11 standard discussed so far are working in the 2.4 and 5 GHz unlicensed frequency bands. In 2012 the IEEE 802.11ad amendment, working in the unlicensed 60 GHz spectrum (mmWave), was released. The PPDU format in IEEE 802.11ad is slightly different from those shown in Fig. 2. OFDM is still employed to transmit data, with $N_{FFT} = 512$, $N_{dsc} = 336$, $N_{cp} = 128$ and a bandwidth of $B = 2.16\ GHz$. However, the preamble is composed of a single–carrier part, which requires a fixed transmission time of 1.89 µs, followed by one OFDM symbol. The packet transmission time of 100 bits packets with IEEE 802.11ad is hence of 2.38 µs (regardless of the modulation order), which is closer to the WirelessHP target of 200 ns.

IV. WirelessHP low–latency PHY

A recent trend in the design of high–rate wireless PHY layers is the adoption of single carrier modulation as an alternative to OFDM [19]. Single carrier transmission has low latency, since it allows stream–, rather than block–, processing, and high energy efficiency, since it has low Peak–to–Average Power Ratio (PAPR). However, in this paper a WirelessHP PHY based on OFDM is proposed, since this modulation technique allows for easier channel equalization, easier compliance to spectrum mask regulations and partial

[2]We assume here that OFDM symbols used in the preamble have the same structure of those used for data, specifically they contain the CP. In some OFDM systems, where preamble symbols do not have a CP, Eq. (4) should be slightly modified.

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TABLE I
TRANSMISSION TIME FOR 100 BITS PACKETS WITH IEEE 802.11 OFDM PHY

Standard	B	N_{FFT}	N_{dsc}	N_{cp}	N_{sym}^{pre}	TX time, T_{pkt}		
						$M=2$	$M=4$	$M=8$
IEEE 802.11a/g	5 MHz	64	48	16	5	128 µs	112 µs	96 µs
IEEE 802.11a/g	10 MHz	64	48	16	5	64 µs	56 µs	48 µs
IEEE 802.11a/g	20 MHz	64	48	16	5	32 µs	28 µs	24 µs
IEEE 802.11n	20 MHz	64	52	16	7	40 µs	36 µs	32 µs
IEEE 802.11n	40 MHz	128	108	32	7	36 µs	32 µs	32 µs
IEEE 802.11ac	80 MHz	256	234	64	10	44 µs	44 µs	44 µs
IEEE 802.11ac	160 MHz	512	468	128	10	44 µs	44 µs	44 µs

reuse of existent designs (e.g., IEEE 802.11). In order to achieve the packet transmission time requirement for low–latency wireless industrial control, an optimized WirelessHP OFDM PHY design has to minimize the inefficiencies that affect short packet transmission in IEEE 802.11.

A. Reducing preamble length

The impact of preamble on PHY layer performance is commonly disregarded in general purpose wireless communications, since its duration is negligible with respect to the entire packet [18]. In short–packet communications, however, the impact of preamble is of primary importance and its duration must be limited as much as possible.

To better clarify this concept, let us define the preamble overhead (in samples) as

$$O_{pre} = N_{sym}^{pre} \cdot \left(N_{cp} + N_{FFT}\right) \tag{5}$$

In IEEE 802.11a/g the preamble overhead is $O_{pre} = 400$ samples, while the total number of samples to transmit a packet of $L = 100$ bits with $M = 8$ is 480, which means that 83% of the transmitted samples are used for preamble.

Reducing the number of preamble symbols, N_{sym}^{pre}, is hence a key step towards the increase of efficiency and the reduction of packet transmission time. However, in order to ensure a reliable packet decoding process, a customized preamble must support the main functions accomplished by the IEEE 802.11 preamble, which are detailed in the following.

- *Packet detection and timing synchronization:* These functions are concerned with identifying the beginning of a packet and achieving sample–level synchronization. The first task is generally realized by exploiting the correlation between repeated identical sequences, such as those contained in the L-STF part of the IEEE 802.11a/g preamble [20]. The second task, accomplished by the L-LTF part, relies on the correlation between the received samples and the known transmitted ones [21].
- *Frequency offset estimation:* Carrier frequency offset (CFO) is a mismatch between transmitter and receiver oscillator frequencies due to Doppler effects and non–idealities of components. OFDM systems are particularly sensitive to CFO, since a strict frequency synchronization is required to ensure subcarriers orthogonality. Hence, an IEEE 802.11a/g OFDM receiver estimates the CFO by exploiting the correlation between repeated identical sequences in both L-STF and L-LTF and compensates for it before decoding.
- *Channel estimation:* This function is concerned with estimating the response of the wireless channel in view of performing channel equalization. In IEEE 802.11a/g, frequency–domain channel estimation is performed by demodulating the received L-LTF symbols and performing element–wise division by the transmitted ones.
- *Information about length and coding:* In order to ensure a correct decoding process, an OFDM receiver must know the length of the PSDU as well as the modulation and coding schemes adopted in the packet generation process. In IEEE 802.11a/g, this information is contained in the SIGNAL (SIG) field of the preamble.

In order to accomplish all the listed functions, the IEEE 802.11 standards use a quite long preamble, as reported in Fig. 2. However, some key assumptions typical of industrial wireless communications can be exploited to design a simplified and reduced preamble still able to carry out all the necessary functions. A central assumption is the predictability of traffic patterns: industrial communications are generally tightly scheduled, as described in Sec. II, and, hence, a node knows with high precision the time instant at which a packet destined to it is supposed to arrive. Consequently, simpler packet detection and timing synchronization algorithms can be designed, that do not need to correlate long sequences. Another important fact is the low temporal variability of the industrial wireless channel [22], which can be exploited to simplify the channel estimation procedures. Finally, the messages exchanged in industrial control applications will be of predefined length and the modulation and coding options are likely to be selected during the network calibration phase and remain fixed [2], hence there is no need of including this information in the preamble of each packet.

The WirelessHP PHY design proposed in this work adopts a reduced preamble of $N_{sym}^{pre} = 1$ symbol, which represents a substantial reduction with respect to the preambles adopted in the IEEE 802.11 standards and reported in Fig. 2. It will be shown in Sec. V that a receiver is able to perform packet detection, timing synchronization, CFO and channel estimation with this one-symbol preamble, by exploiting the mentioned a priori information.

B. Optimizing OFDM parameters

The preamble overhead is not the only source of inefficiency in OFDM communications. There are three other causes of overheads that will be detailed in the following.

- *Cyclic prefix:* every data symbol contains a cyclic prefix of N_{cp} samples, resulting in an overhead of

$$O_{cp} = N_{sym}^{data} \cdot N_{cp} \tag{6}$$

- *Unused subcarriers:* in the OFDM encoding process, the set of subcarriers onto which information bits are mapped does not include all the N_{FFT} subcarriers, as some of them are reserved for special use: N_{psc} pilot subcarriers are used to transmit pilot data employed to correct residual phase errors before decoding; N_{gsc} guard subcarriers at

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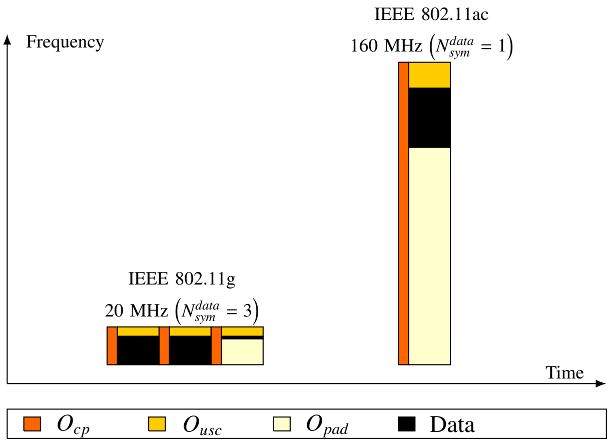

Fig. 3. OFDM overheads in data symbols for IEEE 802.11g (with 20 MHz bandwidth) and 802.11ac (160 MHz). Fixed parameters: $M = 2$, $R_c = 1$, $N_{ss} = 1$, $L = 100$ bits.

the edges of the symbol are nulled in frequency to avoid out–of–band emissions; N_{dcsc} subcarriers in the middle of the symbol are nulled in frequency to avoid Direct Current (DC) offset [23]. The number of data subcarriers can hence be computed as

$$N_{dsc} = N_{FFT} - N_{psc} - N_{gsc} - N_{dcsc} \tag{7}$$

while the overhead due to unused subcarriers is

$$O_{usc} = N_{sym}^{data} \cdot \left(N_{psc} + N_{gsc} + N_{dcsc}\right) \tag{8}$$

- *Padding bits:* the total number of data subcarriers is always $N_{sym}^{data} \cdot N_{dsc}$, but the information bits are mapped only onto $\left\lceil \frac{L}{\log_2 M \cdot R_c \cdot N_{ss}} \right\rceil$ subcarriers, and the two quantities do not necessarily coincide.[3] The subcarriers in excess are padded with zero bits, thus yielding an overhead of

$$O_{pad} = N_{sym}^{data} \cdot N_{dsc} - \left\lceil \frac{L}{\log_2 M \cdot R_c \cdot N_{ss}} \right\rceil \tag{9}$$

Fig. 3 provides a visual representation of the three different sources of overhead in OFDM (cyclic prefix, unused subcarriers and padding bits) versus the amount of modulated data symbols (represented in black), for two extremes of the IEEE 802.11 standard: 802.11g with 20 MHz bandwidth and 802.11ac with 160 MHz bandwidth. It can be observed that the data occupy only a portion of the packet, particularly in IEEE 802.11ac, where the majority of samples (368 out of 640) are wasted for padding.

The WirelessHP PHY proposed in this paper aims at finding the optimal OFDM parameters that can minimize the total packet transmission time. Some parameters cannot be changed because they are imposed by the application (the PSDU size L), by the hardware capabilities (the sampling time T_s and the number of spatial streams N_{ss}), or by preamble design (N_{sym}^{pre}). We also assume that the values of modulation and coding (M and R_c), as well as the number of pilot and DC null subcarriers (N_{psc} and N_{dcsc}), are optimized at a later stage and hence can not be changed here. This leaves only three parameters to be optimized, namely the FFT size N_{FFT}, the cyclic prefix length N_{cp} and the number of guard subcarriers N_{gsc}, yielding the following constrained optimization problem

$$\underset{N_{FFT}, N_{cp}, N_{gsc}}{\arg\min} \; T_{pkt} \tag{10}$$

where T_{pkt} is the quantity expressed by Eq. (4).

The proposed optimization problem is an integer programming problem, as the variable parameters are forced to assume integer values. Moreover, there are a set of constraints to be considered, which are detailed in the following.

- *Cyclic prefix long enough:* the cyclic prefix is inserted before any OFDM symbol to combat ISI in multipath fading channels. In order to do it efficiently, the cyclic prefix duration must exceed the maximum delay spread of the channel [24], i.e.,

$$T_s \cdot N_{cp} \geq T_{ds}^{max} \tag{11}$$

The maximum delay spread depends on the structure of the propagation environment and can be assessed through measurement campaigns.

- *Subcarrier spacing shorter than coherence bandwidth:* the coherence bandwidth of a wireless channel (B_c) is the range over which its frequency response can be considered flat. B_c can be approximated as the inverse of the maximum delay spread [24]. While the overall transmission bandwidth in OFDM is generally greater than the coherence bandwidth, it is important that the channel experienced by a single subcarrier is flat, i.e., $\Delta_{sc} \leq B_c$. Given the subcarrier spacing of $\Delta_{SC} = B/N_{FFT}$, this yields the following constraint on FFT size

$$T_s \cdot N_{FFT} \geq T_{ds}^{max} \tag{12}$$

- *Guard bandwidth large enough:* we define as guard bandwidth ratio the ratio between guard bandwidth, given by $\Delta_{sc} \cdot N_{gsc}$, and the total transmission bandwidth $B = \Delta_{sc} \cdot N_{FFT}$. The standards do not fix an explicit value for the guard bandwidth ratio, as it depends on regulation spectrum masks, OFDM windowing, etc.[4] However, in this paper we assume that all these regulations can be summarized in a minimum guard bandwidth ratio value GBR_{min}, yielding a constraint on the number of guard subcarriers

$$N_{gsc} \geq GBR_{min} \cdot N_{FFT} \tag{13}$$

- *FFT size as a power of 2:* computationally efficient algorithms to perform FFT and its inverse require the number of samples to be a power of 2 [25], hence it must hold

$$N_{FFT} = 2^m, \quad m \in \mathbb{N} \tag{14}$$

The WirelessHP PHY design proposed in this paper is based on the solution of the integer programming problem in Eq. (10) subject to the constraints in Eq. (11), (12), (13), and (14).

[3] For example, if $L = 100$ bits are transmitted with $M = 2$, $R_c = 1$ and $N_{ss} = 1$ in IEEE 802.11ac with 160 MHz bandwidth, they are mapped only onto 100 of the 468 available data subcarriers.

[4] For example, in IEEE 802.11a/g with 20 MHz bandwidth $N_{FFT} = 64$ and $N_{gsc} = 11$, yielding a guard bandwidth ratio of approximately 0.172.

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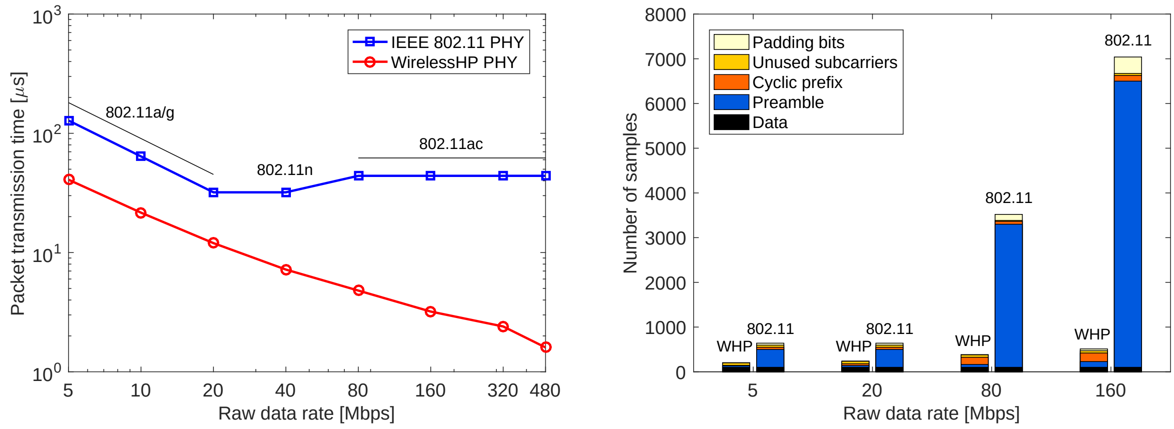

(a) (b)

Fig. 5. Comparison between IEEE 802.11 and WirelessHP (WHP) PHY for L = 100 bits packets and different raw data rates: (a) packet transmission time, (b) breakdown of all transmitted samples per packet, highlighting the overhead.

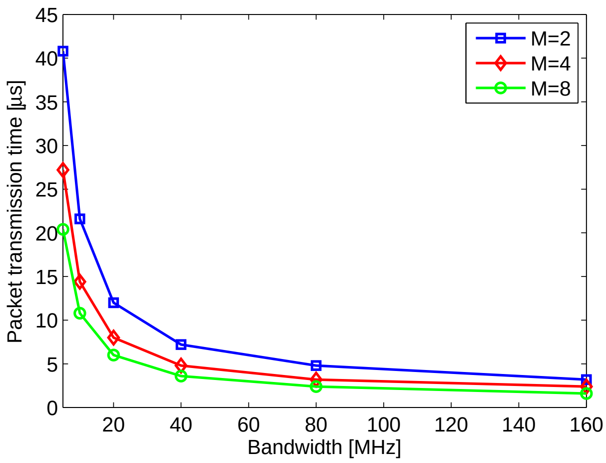

Fig. 4. Packet transmission time in the 2.4/5 GHz WirelessHP PHY for different modulation orders and bandwidth with L = 100 bits packets. A maximum delay spread of T_{ds}^{max} = 400 ns is assumed.

C. Performance with optimized design

The performance of the WirelessHP PHY obtained through the solution of the optimization problem presented in Sec. IV-B and the reduced preamble described in Sec. IV-A are reported here. Some parameters are kept fixed throughout the evaluation described in this and the following sections. Specifically, the PSDU length is fixed to L = 100 bits, a representative value for most critical control applications [2], low–order modulations are employed (M = 2, 4 and 8) to achieve highly–reliable communications, and neither MIMO (N_{ss} = 1) nor channel coding (R_c = 1) are employed, to maintain the structure of the system as simple as possible. Finally, the OFDM parameters (except the FFT size) have been kept close to the values used in the IEEE 802.11g/n standard, i.e., $N_{psc} = 4$, $N_{dcsc} = 1$ and $GBR_{min} = 0.1875$. The first results are relevant to the 2.4/5 GHz spectrum, where the maximum transmission bandwidth is of 160 MHz (in the 5 GHz band only) and a conservative assumption for the maximum delay spread is T_{ds}^{max} = 400 ns (i.e., the minimum guard interval duration in IEEE 802.11n/ac). Finally, the number of preamble symbols is N_{pre}^{sym} = 1, as motivated by the considerations in Sec. IV-A.

Fig. 4 reports the packet transmission time with the WirelessHP PHY for different values of bandwidth (up to the maximum value of 160 MHz) and low–order modulations of $M = 2, 4$ and 8. The curves have been obtained by solving the optimization problem of Eq. (10) and plotting the value of T_{pkt} corresponding to the optimal parameter choice. It can be seen that the WirelessHP packet transmission time scales with the bandwidth (differently from the IEEE 802.11 PHY, as it is reported in Tab. I), reaching the lowest values with B = 160 MHz, of 3.2 µs, 2.4 µs and 1.6 µs for M = 2, 4 and 8 respectively. It can also be observed that the reduction in packet transmission time obtained by increasing the modulation order is significant when the bandwidth is low, while it becomes almost negligible when high transmission bandwidth is available.

The increased efficiency of WirelessHP with respect to the IEEE 802.11 PHY is further analyzed in Fig. 5. The first plot, Fig. 5a, reports the transmission time for L = 100 bits packets versus the raw data rate. This metric, defined as $R = B \cdot \log_2 M$ and measured in bit/s, allows representing modulation and bandwidth simultaneously. The transmission time for such short packets in IEEE 802.11, as it was already reported in Tab. I, does not scale with raw data rate and does not show significant improvements between IEEE 802.11a/g and IEEE 802.11n/ac, as the increased number of subcarriers is compensated by a larger preamble. With the proposed PHY design, instead, the transmission time scales with the raw data rate and reaches almost 1 µs for B = 160 MHz and M = 8, which is almost 28 times lower than what IEEE 802.11ac achieves with the same settings.

A more detailed insight is given by Fig. 5b, which allows to see the role of the transmitted samples, distinguishing between data and the different types of overheads described in Sec. IV-A and IV-B, for selected values of raw data rate. In all

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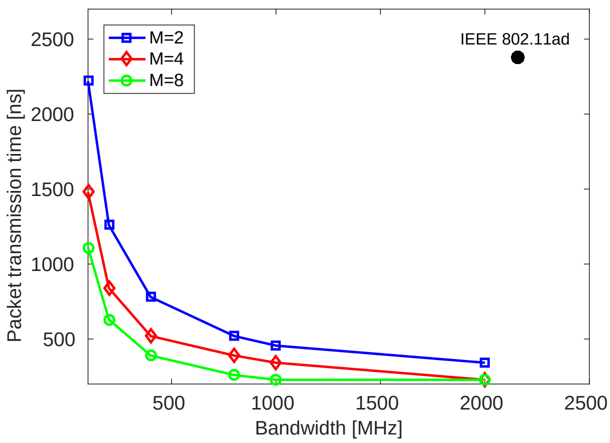

Fig. 6. Packet transmission time in the mmWave WirelessHP PHY for different modulation orders and bandwidth with L = 100 bits packets, compared with packet transmission time in IEEE 802.11ad (same for all modulation and coding schemes). A maximum delay spread of T_{ds}^{max} = 50 ns is assumed.

the considered values the modulation is fixed to M = 2 and, hence, the number of symbols onto which data are mapped is always 100 (for both IEEE 802.11 and WirelessHP). The number of overhead samples, conversely, varies significantly with the data rate and, most notably, with the transition from IEEE 802.11 to WirelessHP. As an example, for R = 160 Mbps, the IEEE 802.11 design requires 6940 overhead samples versus the 371 needed by WirelessHP. Finally, the figure allows to see that the preamble overhead, expressed by Eq. (5), is the major source of inefficiency in IEEE 802.11. In the WirelessHP design, instead, the preamble overhead is more relevant when R is low, whereas the cyclic prefix is the major source of overhead if the raw data rate is high.

In the 2.4/5 GHz spectrum, WirelessHP is able to achieve packet transmission times around 1 µs, which is still 5 times longer than the required value of 200 ns [2]. However, it is not possible to decrease this time even further because of the limited bandwidth and of the high delay spread,[5] which, taking into account the constraints of Eq. (11) and (12), basically force every OFDM symbol to be not shorter than 800 ns. Moving to the mmWave spectrum around 60 GHz would allow to overcome both these limitations. In this frequency band, indeed, an higher transmission bandwidth is available, up to around 2 GHz. Moreover, the delay spread is generally lower than that observed at 2.4/5 GHz, as confirmed by the guard interval duration in IEEE 802.11ad, which is of 48.4 ns compared to the 400 ns in IEEE 802.11n/ac.

Fig. 6 reports the packet transmission time of the WirelessHP PHY for different bandwidth and modulation orders, where all the parameters have been kept to the previous values except the bandwidth (which is equal to the sampling frequency F_s) and the maximum delay spread, fixed to T_{ds}^{max} = 50 ns. It can be observed that again the packet transmission time scales with the available bandwidth, reaching 228 ns (close to the target value for critical industrial control applications) for $B = 2\ GHz$ and $M = 4$ and 8. In comparison, the IEEE 802.11ad PHY, also operating in the mmWave spectrum, requires a bandwidth of $B = 2.16\ GHz$ to achieve a transmission time of 2.38 µs. Similarly to what is shown in Fig. 4, also in the mmWave spectrum the reduction in packet transmission time due to the increase of modulation order is significant when the bandwidth is low and becomes irrelevant for high bandwidth, with $M = 4$ and $M = 8$ yielding the same transmission time if B = 2 GHz is employed.

[5]With more advanced equalization, it would be possible to shorten or omit the cyclic prefix, see e.g., [26]. However, such advanced equalizers are considerably more complex and, hence, will not be considered in this work.

D. Comparison with other industrial wireless solutions

A direct comparison of the WirelessHP PHY with other industrial wireless standards and proposal is not feasible, since the latter include a complete protocol stack, while the former is limited to the physical layer only. However, in order to provide a qualitative comparison, a relation between packet transmission time and scheduling unit for WirelessHP can be stated as

$$T_{SU} = (1 + \eta) \cdot T_{pkt} \tag{15}$$

where η is an overhead (expressed as fraction of the packet transmission time) that accounts for the delays that are not strictly related to the transmission of payload bits, such as propagation time, processing and synchronization margins, ramp-up/ramp-down time, etc. The exact value of η depends on the upper layers that will be designed on top of the proposed WirelessHP PHY, however a typical value can range between 60 and 100%.

The design of the upper layers will also impose the choice of specific parameter values for the WirelessHP PHY, such as modulation order M, code rate R_c, number of spatial streams N_{ss} and bandwidth B. In order to provide an exhaustive representation, we present the SU for a payload of L = 100 bits and three specific set of parameters:

A) A WirelessHP implementation in the 2.4/5 GHz band, with $M = 2$, $R_c = 1$, $N_{ss} = 1$, B = 20 MHz and η = 100% was chosen as the representation of a low–performance system. The optimized parameters $N_{FFT} = 32$, $N_{gsc} = 6$ and $N_{cp} = 8$ yield a packet transmission time of T_{pkt} = 12 µs, and hence a scheduling unit of T_{SU} = 24 µs.
B) A WirelessHP implementation in the 2.4/5 GHz band, with $M = 4$, $R_c = 1$, $N_{ss} = 1$, B = 160 MHz and η = 80% was chosen to represent a medium–performance case. The optimized parameters $N_{FFT} = 64$, $N_{gsc} = 12$ and $N_{cp} = 64$ yield a packet transmission time of T_{pkt} = 2.4 µs, and hence a scheduling unit of T_{SU} = 4.32 µs.
C) A WirelessHP implementation in the mmWave band, with $M = 8$, $R_c = 1$, $N_{ss} = 1$, B = 2 GHz and η = 60% was chosen as the representation of a high–performance system. The optimized parameters $N_{FFT} = 128$, $N_{gsc} = 24$ and $N_{cp} = 100$ yield a packet transmission time of T_{pkt} = 228 ns, and hence a scheduling unit of T_{SU} = 364.8 ns.

The SU achieved with the three proposed WirelessHP implementations (WHP A, WHP B and WHP C) is compared with the slot time of several industrial wireless standards and proposals in Fig. 7. Specifically, we consider WirelessHART (WHART), which has a minimum slot time of 10 ms [8],

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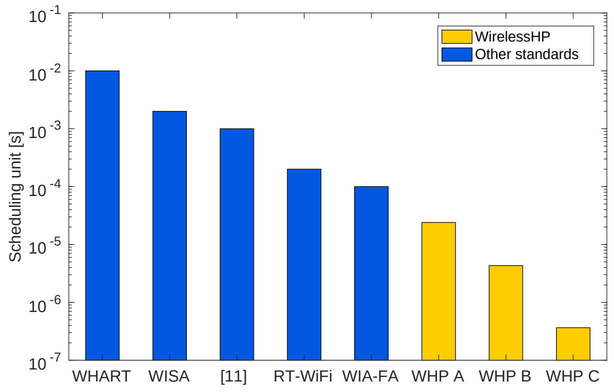

Fig. 7. Scheduling unit (slot time) of WirelessHP implementations versus state–of–the–art industrial wireless standards and proposals.

WISA [12] (2 ms), the modification to IEEE 802.15.4 proposed in [11] (1 ms), the RT-WiFi proposed in [16] (200 µs) and the WIA-FA standard (100 µs).[6]

It can be noticed that implementations based on WirelessHP offer a significant improvement in terms of scheduling unit (and hence latency) with respect to the state–of–the–art industrial wireless solutions (the plot is in logarithmic scale), even when the basic 20 MHz PHY is considered with $M = 2$ modulation and $\eta = 100\%$ overhead (WHP A). Moreover, it is evident that the migration to the mmWave spectrum (implementation WHP C) allows a notable reduction of scheduling unit, allowing to approach very closely the target of 200 ns.

V. Experimental validation

The WirelessHP PHY layer design presented in Sec. IV has been implemented on an experimental demonstrator based on SDR platforms. Although the adopted hardware was limited to work in the sub–4 GHz spectrum and with a very low bandwidth of 5 MHz, the obtained results provide a first proof of the feasibility of the proposed design.

The experimental setup adopted in this paper is schematically represented in Fig. 8. Two Ettus Universal Software Radio Peripherals (USRPs) model N210, each mounting an SBX-40 daughterboard allowing operations in the 0.4-4.4 GHz band, are used to setup a unidirectional wireless link. Each USRP is connected to a Windows PC through a Gigabit Ethernet cable. Two Matlab programs were developed to run on the Windows PCs: `OFDM_TX` handles the generation and encoding, while `OFDM_RX` performs the baseband processing and decoding of WirelessHP packets. For debugging purposes, a Tektronix MDO4104-6 oscilloscope is attached to the antenna of the transmitting USRP through a power splitter and a Rohde&Schwarz FSH6 spectrum analyzer is employed to monitor the wireless medium.

The USRP N210 platforms employ a Xilinx Spartan 3A-DSP FPGA module which performs digital/analog conversion and sample buffering, but cannot perform the baseband processing. This limitation, coupled with the limited real–time

[6] The WIA-FA standard does not specify a minimum slot time, however some preliminary implementations reported a value of 100 µs.

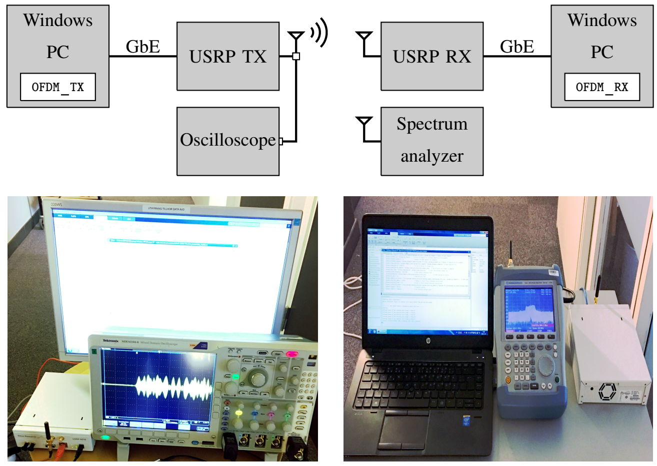

Fig. 8. Narrowband experimental demonstrator based on USRP N210.

performance of the Windows PCs, restricted the achievable sample frequency F_s and hence the bandwidth B. Indeed, with the considered setup, it was only possible to run the tests at $B = 5$ MHz. At the receiving side, time domain samples were recorded and processed at non–real–time speed, due to the limited processing power of the PC. In order to avoid interference from other co–located WLANs, the tests were performed in the 868 MHz unlicensed spectrum, where a conservative assumption of $T_{ds}^{max} = 400$ ns was considered for the delay spread.

During the tests, the transmitting node sent WirelessHP packets with a PSDU size of $L = 104$ bits and a repetition period of $T = 100$ µs. The values of the other PHY layer parameters were mostly the same as in the theoretical evaluation carried out in Sec. IV: a single spatial stream ($N_{ss} = 1$), $N_{psc} = 4$ pilot subcarriers, $N_{dcsc} = 1$ DC null subcarrier and a minimum guard bandwidth ratio of $GBR_{min} = 0.1875$. While in the theoretical analysis channel coding was not considered, here a high–rate convolutional channel coding scheme was applied ($R_c = 5/6$), which, however, did not influence the results in terms of packet transmission time since the additional bits used for coding would be padded if coding were not employed. Only low–order Phase–shift Keying (PSK) modulations were considered, namely BPSK ($M = 2$), QPSK ($M = 4$) and 8-PSK ($M = 8$). The optimized packet durations obtained through the WirelessHP design are $T_{pkt} = 47.6$ µs, 27.2 µs and 20.4 µs for BPSK, QPSK and 8-PSK respectively. These values were obtained by using an optimized FFT size of $N_{FFT} = 32$ with $N_{gsc} = 6$ guard subcarriers and $N_{cp} = 2$ samples for cyclic prefix.

A first set of results is presented in Fig. 9, where the waveforms captured by the oscilloscope when BPSK and 8-PSK were used for the transmission of WirelessHP packets are presented. The figure also includes the waveforms obtained if the IEEE 802.11g PHY were used instead of the proposed

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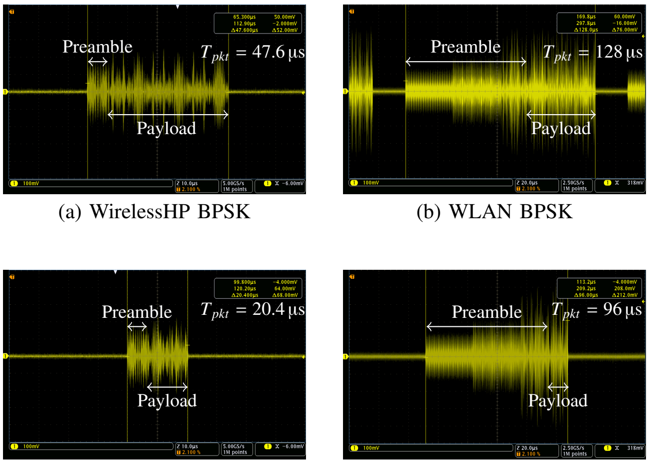

(a) WirelessHP BPSK
(b) WLAN BPSK
(c) WirelessHP 8-PSK
(d) WLAN 8-PSK

Fig. 9. Captured WirelessHP and WLAN (IEEE 802.11g) waveforms for L = 104 bits packets transmitted with BPSK and 8-PSK with 5 MHz bandwidth. Please note that the zoom level in the WLAN waveforms (b) and (d) is doubled with respect to the WirelessHP waveforms (a) and (c).

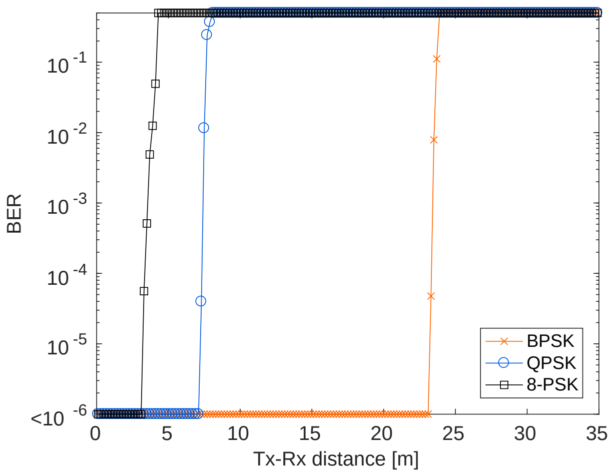

Fig. 10. BER vs. communication distance for the 5 MHz WirelessHP PHY with different low–order modulations. Each measurement involved the transmission of 10^4 packets of 104 bits.

one.[7] It can be noticed that there is a significant reduction in packet transmission time from IEEE 802.11 to WirelessHP: almost 3 times for BPSK (47.6 µs vs. 128 µs) and almost 5 times for 8-PSK (20.4 µs vs. 96 µs). The decrease in packet transmission time is in great part due to the reduction of the preamble, which can be observed to be quite dominant in the IEEE 802.11 waveforms (especially when 8-PSK is employed).

The reliability level of the proposed WirelessHP PHY is presented in Fig. 10, which shows the results of an experimental campaign aimed at assessing the Bit Error Rate (BER) at different communication distances. In order to perform this campaign, a total of 10^4 WirelessHP packets (i.e., more than 10^6 payload bits) have been sent for each modulation order M and for different distances between transmitter and receiver, ranging from 0 to 35 meters with 0.2 meters granularity. The results show that the lowest modulation (BPSK) is able to achieve zero errors (which indicates a BER lower than 10^{-6}) up to more than 20 meters, whereas QPSK and 8-PSK show zero errors only up to 7 and 4 meters respectively. These results confirm that the proposed PHY is able to guarantee reliable communication within the short–range applications envisioned by the WirelessHP scenario. Specifically, it is confirmed that a preamble of only one OFDM symbol is sufficient to support reliable packet reception.

A further experimental result, presented in Fig. 11, is concerned with the robustness of the proposed WirelessHP PHY to carrier frequency offset. In order to perform this test, a controlled mismatch was artificially inserted between the center frequencies of the transmitting and receiving USRPs, with a maximum value of ±45 ppm. The tests have been performed with a fixed distance between transmitter and receiver of 1.5 meters and again involved the transmission of 10^4 packets for each frequency offset and modulation value. The results show that all the considered modulations do not exhibit any significant error until roughly ±30 ppm, which represents a good robustness level.[8] When an higher offset is introduced, the higher–order modulation (8-PSK) is the most sensitive to synchronization errors, as expected.

VI. Conclusions, limitations and future directions

This paper proposes a low–latency PHY layer for high–performance wireless industrial control applications (named WirelessHP), specifically aimed at reducing latency through the minimization of transmission time for very short packets. The design is based on the IEEE 802.11 OFDM PHY, but it is significantly optimized by both reducing the PHY layer preamble and optimizing the OFDM parameters. Theoretical analysis shows that the proposed PHY is able to greatly reduce the packet transmission time with respect to IEEE 802.11, down to almost 1 µs in the 2.4/5 GHz band and 200 ns in the mmWave band for 100 bits packets. The feasibility of the proposed design is confirmed through an SDR–based experimental demonstrator. With this platform, reliable communication can be established up to 20 meters distance if BPSK is employed.

However, this demonstrator platform has several limitations. As a first issue, the current SDR demonstrator is only able to work at a limited bandwidth (5 MHz), which does not allow a significant reduction of the packet transmission time. Upgrading the available hardware would allow to increase the bandwidth and speed up the packet exchange by performing all the baseband processing in the FPGA. Moreover, when the scheduling unit becomes very short (some µs), the packet transmission time may not be the dominant source of delay and some other aspects, such as synchronization and processing times, must be managed. Furthermore, if operation in

[7] In order to provide a fair comparison, the same bandwidth B = 5 MHz was used for WirelessHP and IEEE 802.11g: the parameters for IEEE 802.11g with 5 MHz bandwidth are reported in the first row of Tab. I. Due to the increased packet transmission time with IEEE 802.11, the packet transmission period has also been increased from 100 µs to 150 µs.

[8] It has to be noted that devices compliant to the IEEE 802.11 standard in the 2.4 GHz band must have a maximum tolerance on clock frequency of ±20 ppm [14].

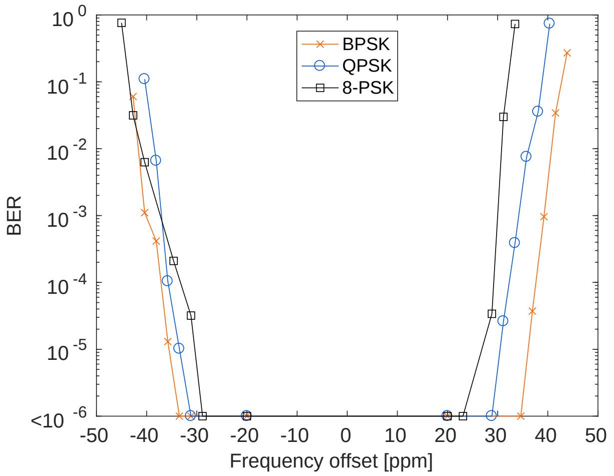

Fig. 11. BER vs. artificially introduced frequency offset between transmitter and receiver oscillators for the 5 MHz WirelessHP PHY with different low–order modulations and a fixed communication distance of 1.5 meters.

the mmWave band is considered, directional communication should be established through beamforming techniques in order to overcome the high path–loss, requiring the development of high–accuracy beamforming strategies. Finally, the reliability level reported in this paper (BER lower than 10^{-6}), although high, may not be good enough for the most critical industrial applications, which could require a BER of 10^{-10} or lower. In order to achieve this target, methods for increasing reliability should be considered, such as enhanced channel coding, spatial diversity schemes, improved channel estimation and synchronization algorithms and optimized analog Radio–Frequency (RF) front end stages. The effect of packet size on reliability will also be investigated by taking into account other possible packet lengths typical of specific industrial control scenarios.

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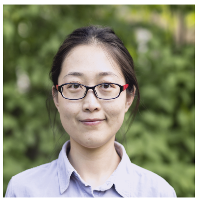
Michele Luvisotto received the Masters degree in automation engineering from the University of Padova, Padova, Italy, in 2014. He is a PhD student with the Department of Information Engineering, University of Padova, Padova, Italy. He has been a visiting researcher at ABB Corporate Research Center in Västerås (Sweden) from March to September 2016. His research interests include wireless networks and real-time industrial communication.

Zhibo Pang received B.Eng. in Electronic Engineering from Zhejiang University, Hangzhou, China in 2002, MBA in Innovation and Growth from University of Turku, Turku, Finland in 2012, and PhD in Electronic and Computer Systems from the Royal Institute of Technology (KTH), Stockholm, Sweden in 2013. He is currently a Principal Scientist and Project Manager on Industrial IoT at ABB Corporate Research, Vsters, Sweden, leading research projects on digitalization solutions for smart homes and buildings, factory and manufacturing, and power systems. He is also serving as Adjunct Professor or similar roles at universities such as Royal Institute of Technology (KTH), Sweden, Tsinghua University, China, and Beijing University of Posts and Telecommunications (BUPT), China. He serves as Chair of Sub TC in the Technical Committee on Industrial Informatics, Industrial Electronics Society of IEEE. He is Associate Editor of IEEE Transactions on Industrial Informatics, IEEE Journal of Biomedical and Health Informatics, and IEEE Review on Biomedical Engineering; Guest Editor of IEEE Access; and Editorial Board of Journal of Management Analytics (Taylor & Francis), Journal of Industrial Information Integration (Elsevier), and International Journal of Modeling, Simulation, and Scientific Computing (WorldScientific). His current research interests include the Industry4.0, real-time cyber physical systems, Internet-of-Things, wireless control network, industrial communication, real time embedded system, high accuracy localization and navigation, enterprise systems, automation and robotics, multicore system-on-chip and network-on-chip. He also works on the business-technology joint research such as strategy, business model, value chain, and entrepreneurship and intrepreneurship.

Dacfey Dzung received the M.Sc. and Ph.D. degrees in Electrical Engineering from the Swiss Federal Institute of Technology (ETH) in 1975 and 1981, respectively. He has been with Brown-Boveri, Alcatel, Ascom, Bosch Telecom, and since 1997 he is with ABB Corporate Research, Baden, Switzerland, where he is now an ABB Corporate Research Fellow in Industrial and Utility Communication. He has worked on a variety of communication systems, including satellite and cellular mobile radio, industrial wireless sensors, and powerline communications. His main technical contributions are in the design of communication protocols and of modem signal processing algorithms. He has also studied cyber security issues in industrial and utility communication systems. His current technical interest is in communication networks for Factory Automation, Process Automation, and the Smart Grid, with focus on networks using heterogeneous technologies such as wireless and powerline communications. Dr.Dzung was member of the working groups of the European Telecommunication Standards Institute (ETSI) specifying the digital cellular standard GSM, digital microwave links (RES), and the trunked mobile radio system TETRA. Currently he is member of the IEEE P1901.2 working group on narrowband powerline communication, Swiss national delegate to the IEC working group SC65c/WG16 on industrial wireless networks, and member of ETSI and CENELEC working groups on standardization and regulation of industrial wireless applications. Dr.Dzung has served as Associate Editor of the IEEE Transactions on Industrial Informatics, and is in the program committees of the conference series on Emerging Technologies and Factory Automation (ETFA) and Workshops on Factory Communication Systems (WFCS).

Ming Zhan received the Ph.D. degree from the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu, China, in 2013. He is currently an Associate Professor with the College of Electronics and Information Engineering, Southwest University, Chongqing, China. He is currently involved in the architecture design of low-complexity and energy-efficient turbo code decoder, high performance wireless communications in industrial automation.



Xiaolin Jiang received the M.Sc. degree in Information and Communication Engineering from Harbin Institute of Technology, Harbin, China in 2015. She is now a PhD student at the Department of Network and Systems Engineering at Royal Institute of Technology (KTH), Stockholm, Sweden. Her research interests include wireless networks, low latency communication and millimeter wave communication.