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Postprint

This is the accepted version of a paper published in *IEEE Journal on Selected Areas in Communications*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Jiang, X., Pang, Z., Zhan, M., Dzung, D., Luvisotto, M. et al. (2019)
Packet Detection by a Single OFDM Symbol in URLLC for Critical Industrial Control: A Realistic Study
IEEE Journal on Selected Areas in Communications, 37(4): 933-946
<https://doi.org/10.1109/JSAC.2019.2898761>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-248321>

Packet Detection by a Single OFDM Symbol in URLLC for Critical Industrial Control: a Realistic Study

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Abstract—Ultra-high reliable and low-latency communication (URLLC) is envisaged to support emerging applications with strict latency and reliability requirements. Critical industrial control is among the most important URLLC applications where the stringent requirements make the deployment of wireless networks critical, especially as far as latency is concerned. Since the amount of data exchanged in critical industrial communications is generally small, an effective way to reduce the latency is to minimize the packet's synchronization overhead, starting from the physical layer (PHY). This paper proposes to use a short one-symbol PHY preamble for critical wireless industrial communications, reducing significantly the transmission latency with respect to other wireless standards. Dedicated packet detection and synchronization algorithms are discussed, analyzed and tuned to ensure that the required reliability level is achieved with such extremely short preamble. Theoretical analysis, simulations and experiments show that detection error rates smaller than 10^{-6} can be achieved with the proposed preamble while minimizing the latencies.

Index Terms—packet detection, URLLC, differential detection, transmission prediction, USRP validation.

I. INTRODUCTION

Ultra-high reliable and low-latency communication (URLLC) is proposed to support transmissions characterized with short packet size, low latency (ranging from one to a few milliseconds end-to-end latency) and high reliability (higher than 99.999%) [1]. Among the dominant URLLC scenarios, industrial control applications pose crucial requirements to the underlying communication network including high reliability, determinism, reduced latency, and support for higher security [2]–[4]. In the industrial sites, wireless networks are gaining popularity because they offer simple deployment, mobility support and low cost [5]. When considering the most critical industrial applications, latency appears to be the most difficult requirement to satisfy [6].

In order to minimize the latency in the exchange of small-size packets, it is fundamental to reduce the control overhead, which is not negligible as in traditional communications [7]. The most relevant and crucial part of such an overhead are the

preamble symbols, which are transmitted at the beginning of each packet. These symbols are then exploited at the receiver to ensure accurate detection and synchronization. Though the industrial control applications pose stringent latency and reliability requirements, they are also characterized with periodic and deterministic traffic pattern. It is hence fundamental to carefully take advantage of their characteristics for the preamble structure and the detection algorithms design, striking a tradeoff between minimizing the latency and ensuring high reliability in critical industrial applications.

There is a rich history of research concerning PHY packet detection, time-frequency synchronization and channel estimation. The estimate of the optimal location of the PHY synchronization symbols is studied in [8], which considers both the correlation and energy correction procedures for such estimation. To guarantee high reliability in the packet detection, an adaptive beacon transmission strategy is proposed in [9] to switch between narrow band interference and wide band interference. A packet detection based on IEEE 802.15.4 PHY for low power IoT networks is proposed in [10], where differential encoding is applied to reduce false alarm probability, and therefore reducing the power consumption. [11], [12] investigate differential preamble detections in direct-sequence spread-spectrum (DSSS) system at chip-level and at sample level, and differential detection is claimed to have superior performance in channels with frequency offset. [13] proposes to improve the reliability at DSSS chip level of IEEE 802.15.4, however, the packet preamble is exempt from the protocol. In cellular standards with TDMA Medium Access Control, timing advance is used by the base station to control the signal delay of the multiple mobile devices with different distances to avoid collisions [14], [15].

However, the studies above and the relevant wireless standards adopt a long preamble. For example, the preamble of IEEE 802.11 [16] is divided into a primary and secondary part, to achieve packet detection, time-frequency synchronization and channel estimation. Such a long preamble is a major hinder to low-latency communications. Therefore, in this paper, we investigate the new hypothesis whether the use of a very short preamble composed of just one orthogonal frequency-division multiplexing (OFDM) symbol (compared to the 5 or more symbols used in IEEE 802.11) can minimize the overall latency, while preserving an adequate performance in terms of packet detection and synchronization. To assess this hypothesis, we study two packet detection algorithms that allow our proposed preamble to achieve similar performance to the longer preamble used by IEEE 802.11 in industrial applications. Our algorithms include differential detection and

Manuscript received June 22, 2018; revised December 3, 2018.

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a transmission prediction mechanism which exploits the predictability of industrial traffic, acting as a coarse packet timing acquisition while also reducing the computational load and energy consumption. The algorithms are then analyzed and tuned through theoretical analysis, numerical simulations and experiments in a realistic factory environment. The results show that the differential detection algorithm requires in general higher SNR than the non-differential algorithm, but it is robust to a much wider range of frequency offsets. The transmission prediction mechanism is instead effective to reduce the false alarms caused by external interfering bursts.

In summary, the main contributions and innovations of this paper are summarized as follows:

- 1) We propose for the first time to use an extremely short preamble (one OFDM symbol) with the aim of minimizing latency in critical industrial applications while maintaining all the functions of packet detection, automatic gain control (AGC), frequency offset and channel state information estimation;
- 2) We present a possible architecture for reliable packet detection with the proposed short preamble that adopts two established mechanisms (differential detection and transmission prediction);
- 3) We assess the performance of the proposed short preamble by experiments in a real factory setting.

The rest of the paper is organized as follows: In Section II we introduce the background and present the gap between the existing industrial communication protocols and the stringent requirements of critical industrial applications. The new preamble design and the relevant algorithms are described in Section III, and the theoretical analysis together with simulation results is presented in Section IV. The experimental results are shown in Section V, whereas Section VI concludes the paper and discusses future works.

II. BACKGROUND OF WIRELESSHP AND RELATED WORKS

The required performance for industrial wireless networks varies depending on the physical processes that are monitored and/or controlled. For example, by supervising the production activities, process automation aims at more efficient and safe operations of (for example) paper, mining and cement processes [3], [17]. Factory automation, instead, includes the critical applications in the factory, such as motion control and programmable logic controllers operation [18]. Finally, power systems automation refers to automatically monitoring, controlling, and protecting the power system via instrumentation and control devices [19], and power electronic control deals with the synchronized control of power electronics devices [20].

The qualitative demands of these industrial scenarios can be transformed into quantified requirements, including update rate, number of the nodes, and packet error rate (PER). To further evaluate the latency level of different scenarios, the scheduling unit (i.e., the minimum time in which a packet can be exchanged between a controller and a sensor/actuator node) is also considered as a requirement [6]. With the rough assumptions of no multiplexing in the space and frequency

TABLE I
THE REQUIREMENTS FOR DIFFERENT INDUSTRIAL SCENARIOS [6] (PA: PROCESS AUTOMATION, FA: FACTORY AUTOMATION, PSA: POWER SYSTEMS AUTOMATION, PEC: POWER ELECTRONIC CONTROL, SU: SCHEDULING UNIT)

Scenario	Update Rate	# of Nodes	SU	PER
PA	0.1-1 s	$10^2 - 10^3$	~ 1 ms	10^{-6}
FA	1-10 ms	$10^2 - 10^3$	~ 10 μ s	10^{-6}
PSA	0.1-1 ms	$10^1 - 10^2$	~ 1 μ s	10^{-9}
PEC	10-100 μ s	$10^2 - 10^3$	~ 100 ns	10^{-9}

domain, and no redundancy in the time domain, the scheduling unit can be calculated by dividing the update rate by the number of nodes. Scheduling unit can be easily modified by multiplying a factor when multiplexing/redundancy is available. For example, the medium voltage converter described in [20] is composed by 48 cells and governed by a control system whose cycle time is 100 μ s. Hence, the scheduling unit for each cell is around 2 μ s. Another example, related to factory automation, is represented by the distributed control platform described in [18], where the cycle time is 30 μ s with 3 nodes, hence the transmission time for each node should be less than 10 μ s. Representative requirements of the aforementioned industrial scenarios are listed in Tab. I [6].

It can be observed how, besides the high reliability, the most critical scenarios, such as factory automation, power systems automation, and power electronics control, also set stringent delay requirements with scheduling unit ranging from hundred nanoseconds to tens of microseconds. Reviewing the existing wireless technologies, there are large gaps between their performance and the aforementioned scheduling unit requirements. For example, WirelessHART [21], ISA 100.11.a [22] and WIA-PA [23], are which built on the IEEE 802.15.4 WPAN physical (PHY) layer and rely on timeslotted channel hopping, achieve a 10 ms slot time (scheduling unit). Siemens iWLAN [24], built on IEEE 802.11 and using industrial Point Coordination Function for medium access in real-time applications, achieves 2 ms scheduling unit. WISA [25], built on IEEE 802.15.1 and exploiting time division multiple access (TDMA) and frequency hopping schedules 128 μ s and 64 μ s for uplink and downlink scheduling units respectively. WIA-FA [26], built on IEEE 802.11 and relying on TDMA achieves a 100 μ s scheduling unit.

Due to this notable performance gap, the most critical industrial applications are currently served through wired real-time Ethernet networks, such as EtherCAT [18], [20], even if the potential benefits offered by wireless connectivity would be significant. The recently proposed WirelessHP (High Performance) aims to provide a wireless solution for critical industrial applications, offering multi-Gbps aggregate data rate, very high reliability level range from 10^{-6} to 10^{-9} , and scheduling unit lower than 1 μ s [27]. However, in the works published so far, the analysis of the preamble structure and performance is not well discussed. As the preamble design is crucial to strike the tradeoff between latency and reliability when using short packets, we investigate the possibility of using just one preamble symbol to satisfy the targets of WirelessHP.

The packet detection methods reviewed in Section I fail to satisfy the scheduling unit requirement for WirelessHP, and the standards on which they are based on are far from supporting multi-Gbps aggregate data rate. The Wireless Local Area Network (WLAN) described in the IEEE 802.11 standard [16], works as the base for recent industrial standards to support high data rates [26], [28], with the common practice being to upgrade the data-link and higher layers to ensure deterministic communications. However, in the most critical scenarios, revisions in the physical layer are also needed, as the preamble duration is too long for ultra low latency applications.

To provide an example, let us consider the IEEE 802.11a/g standard, in which the preamble consists of 10 repeated short symbols (SSs) and 2 repeated long symbols (LSs) based on OFDM with FFT size being 64 [16]. Each SS employs 12 subcarriers and has 16 samples, and is used for signal detection, AGC, timing synchronization and coarse frequency offset estimation. Among the above functions, signal detection exploits the correlation of the repeated pattern of SSs by the Schmidl and Cox's method [29], and timing synchronization can be done by the cross-correlation with the known SS sequence [30]. The LSs occupy 52 subcarriers (48 for data and 4 for pilot), and 64 samples. The LSs are used for channel estimation and fine frequency offset estimation. Together with a 32-sample guard interval appended to the front of the LSs, the preamble has 320 samples in total, and the duration is 16 μ s for 20 MHz bandwidth (channel spacing), which is quadrupled to 64 μ s for 5 MHz bandwidth. By comparison with Tab. I, it can be seen that, in the most critical scenarios, the preamble duration alone exceeds the scheduling unit (which also includes data transmission, acknowledgement, synchronization margins, etc.). It is worth to underline that IEEE 802.11a/g has the shortest preamble in the WLAN family, with the most recent standards (e.g., IEEE 802.11ac) employing longer preamble sequences and, hence, failing to reduce packet duration below 40 μ s. Further details are reported in Section IV.

III. PREAMBLE DETECTION IN WIRELESSHP

Before describing the receiver architecture for preamble detection, it is worth describing the major features of the industrial communication scenarios. Indeed, while critical industrial scenarios present strict requirements in terms of reliability, data rate and latency, they also have some properties that allow reducing preamble size, while still performing accurate detection and synchronization. In many relevant industrial applications, for example, the traffic is periodic and deterministic, due to the fact that sensing data and actuation commands, which carry real-time information, must be available at precise time instants. Moreover, the packet size can be fixed, as the content usually follows a fixed structure. In the majority of industrial applications, the number of nodes is known and most of the nodes are mounted at fixed positions. Under few scenarios, the nodes are mounted on the moving objects, for example, robots over automated guided vehicles. However, in these cases the nodes do not perform critical tasks when they

Fig. 1. Illustrative TDMA structure: the upper figure shows two TDMA cycles with five nodes; the lower figure reports the activity of a single node during the different cycles and an external interference from another transmitter. White spaces between TDMA slots represent synchronization margins.

are moving, and they only start to work when they have arrived at the designated locations. On the other hand, the surrounding environment keeps changing during processes due to the moving objects around. Quasi-static channels are assumed where the devices and machines are static or with limited mobility. This assumption is relevant for prominent use cases such as intelligent electronic devices in substation automation, and power electronics control [20]. The importance of these use cases is clearly identified in the WISA standard [25].

In order to ensure deterministic data exchange of periodic traffic flows, industrial communications generally use TDMA at the data-link layer, as shown in the upper part of Fig. 1. The TDMA cycle is divided in slots (whose duration equals the scheduling unit) and, within each slot, the transmission of a packet by a specific node occurs, which includes the time needed for transmitting the preamble, the data, and a margin to avoid synchronization problems. The lower part of Fig. 1 shows the channel usage from the perspective of a single node.

A. Preamble functions and receiver architecture

The proposed preamble architecture works in wireless systems where OFDM modulation is used. In this framework, the preamble occupies one OFDM symbol whose FFT size, cyclic prefix (CP) length, and subcarriers usage are the same as the symbols employed for data transmission. The data carried in each subcarrier of the preamble symbol are fixed and known to the receiver, and they are employed to perform packet detection, AGC, frequency offset estimation and channel estimation.

Specifically, packet detection is the first operation to be carried out and will be discussed in detail in the remainder of this section. After that, the AGC adjusts the receiver gain by calculating the signal power after packet detection, and, as the channel is assumed to be quasi-static, a smoothing filter can be used to adjust the receiver gain. The frequency offset is estimated by exploiting the correlation between the CP and the last part of the preamble symbol. Finally, the channel state information in the frequency domain can be estimated by FFT of the preamble samples. All the functions carried by our single preamble symbol are applied to the payload data immediately following in the same packet. When a new packet is detected in the next communication cycle, all the functions are performed again. Moreover, since the proposed

Fig. 2. Block diagram of packet detection at the receiver. The upper block illustrate the data flow at radio front end for packet detection, AGC, and decoder, while the details of the packet detection are shown in the block below.

TABLE II
DEFINITIONS USED IN THE DETECTION ALGORITHMS

C	correlation value
L	preamble sequence length
M	detection metric
$\mathbf{p}_{ L \times 1 }$	reference preamble sequence
$\mathbf{r}_{ (L-1) \times 1 }$	differential reference preamble sequence
$\mathbf{x}_{ L \times 1 }$	received sequence
$\mathbf{y}_{ (L-1) \times 1 }$	differential received sequence

algorithms are similar to those applied in IEEE 802.11 but the preamble size is much lower, the overall processing time of our algorithm will be much shorter than that of IEEE 802.11.

Packet detection, discussed in this paper, is the most important function of the preamble, as the other functions as well as the following decoding of the data symbols rely on its success and accuracy. We define detection error rate (DER) as the error rate of packet detection, and the errors can consist of missed detection (the data packet is present, but the receiver fails to detect it) or false alarm (the receiver announces the start of a packet when there is no packet present). In this paper, we consider transmission prediction and differential detection to reduce the DER, as described in detail in the remainder of this section. The upper part of Fig. 2 shows the block diagram of an experimental receiver, and the details of the proposed packet detection process are expanded in the part below. The parameters that will be used in this section and the next section are listed in Table II.

B. Transmission Prediction

In the critical control applications considered in this paper, a star topology with TDMA is adopted. In this context, as it can be seen in the lower part of Fig. 1, the time at which a specific node transmits or receives a packet is fixed and known, while the rest of the TDMA cycle is idle. Consequently, each receiving node can predict the instant in which the corresponding transmitter will start the transmission process and activate packet detection only during this time. Thanks to this strategy, called “transmission prediction”, possible interfering signals

arriving outside of the predetermined slots (as shown in the figure) will not cause false alarms.

The transmission prediction mechanism acts as a sort of coarse packet timing acquisition, then cross-correlation can be applied directly for fine timing synchronization, as discussed in the next subsection. For the non-differential detection algorithm, the received samples are sent to a buffer having the size equal to the reference preamble sequence, and cross-correlated with this sequence. If the correlation value is larger than the set threshold, the detector claims the presence of a packet; otherwise, it slides the content in the buffer by one sample, and perform again the above procedure. For the differential detection algorithm, the Hadamard product of the received sample sequence and its one-sample-delayed sequence is sent to the same buffer. The reference differential preamble sequence is obtained as the Hadamard product of the reference non-differential preamble sequence and its one-sample-delayed sequence. Then, the detector compares the correlation value between the differentiated received samples in the buffer and the reference differential preamble sequence with the threshold to determine the presence of a packet. As shown in the block diagram below in Fig. 2, once a packet is detected, the start of the preamble is determined at the sample level. As the number of symbols and the samples in each symbol are fixed and known, all the samples of the preamble and data symbols are then collected and sent to the decoder for further processing. The main benefit of the prediction mechanism is to reduce the occurrence of false alarms when there is interference with similar preamble patterns, which will be discussed in Subsection V-C. Moreover, by turning off packet detection when it is not needed, this mechanism also effectively reduces the computation and power consumption at the receiver side.

C. Non-differential Detection

Non-differential detection is performed by the cross correlation between the reference preamble sequence and the received samples. For the reference sequence design, we chose to adopt a pseudo noise (PN) sequence in accordance with the WLAN protocols to support continuity and due to its good correlation properties [16]. The PN sequence is then modulated using BPSK without coding and allocated on the preamble subcarriers. To this aim, a time-domain preamble sequence $\mathbf{p}$ is generated using IFFT, and the length of the preamble samples is $L = N_{\text{FFT}} + N_{\text{CP}}$. Alternatively, the PN sequence could be directly applied as a time domain preamble sequence $\mathbf{p}$.

The reference preamble sample sequence $\mathbf{p}$ is stored at the receiver side, and cross correlation between $\mathbf{p}$ and the received samples $\mathbf{x}$ is computed for packet detection:

$$C^{\text{ND}}(k) = \sum_{m=0}^{L-1} \bar{\mathbf{p}}(m) \mathbf{x}(k+m), \quad (1)$$

where $\bar{\cdot}$ denotes complex conjugate, and the superscript ND is short for non-differential detection. If the correlated value is larger than the threshold, then a packet is announced to be present, and the first sample of the preamble is also

determined. As the correlated value is also related to the amplitude of the received signal, to get a unified threshold, we define the detection metric

$$M^{\text{ND}}(k) = \frac{|\sum_{m=0}^{L-1} \bar{\mathbf{p}}(m) \mathbf{x}(k+m)|^2}{\|\mathbf{p}\|^2 \|\mathbf{x}\|^2} = \left| \sum_{m=0}^{L-1} \frac{\bar{\mathbf{p}}(m)}{\|\mathbf{p}\|} \frac{\mathbf{x}(k+m)}{\|\mathbf{x}\|} \right|^2, \quad (2)$$

where $\|\cdot\|$ represents Euclidean norm. In this way, the detection metric is normalized to 1, and (2) is the correlation between the reference $\mathbf{p}$ and the received sample sequence, regardless of the received signal power.

As the numerator and denominator of $M^{\text{ND}}(k)$ in (2) both contain the random variable $\mathbf{x}$, it is difficult to derive the exact distribution of $M^{\text{ND}}(k)$, we therefore need to have an approximation of adequate tractability. In the denominator of (2), by replacing $\|\mathbf{x}\|^2$ with its expected value, $M^{\text{ND}}(k)$ can be approximated as

$$M_{\text{appr}}^{\text{ND}}(k) = \frac{|\sum_{m=0}^{L-1} \bar{\mathbf{p}}(m) \mathbf{x}(k+m)|^2}{\|\mathbf{p}\|^2 \mathbb{E}[\|\mathbf{x}\|^2]}. \quad (3)$$

The accuracy of the approximation is validated by simulation in Subsection IV-C, where we compare the missed detection probability and false alarm probability of the detection algorithm based on (2) with the corresponding probabilities calculated from the distribution of the approximation (3).

D. Differential Detection

The presence of frequency offset is harmful to the packet detection, and it is usually inevitable for two reasons. The first is due to the fact that the local oscillator at the receiver side can not be identical to the one at the transmitter side. The second reason is the Doppler effect caused by the moving of the receiver and/or transmitter. This offset is typically estimated and corrected before decoding, but at the time of packet detection it is still present.

Suppose there is a frequency offset Δf between the transmitter side and the receiver side, and, neglecting the AWGN noise, the received sequence is

$$\mathbf{x}(k) = \mathbf{p}(k) e^{j2\pi k \Delta f \tau}, \quad (4)$$

where τ is the sample duration. The frequency offset causes an increasing phase offset $2\pi k \Delta f \tau$ to the k th sample in $\mathbf{x}$, which decreases the correlated value between $\mathbf{x}$ and $\mathbf{p}$ and may result in missed detection. The value of the phase offset is determined by the frequency offset Δf and the sample duration τ .

To make packet detection more robust to frequency offset, the detection can be performed in a differential way. To this aim, the received sequence $\mathbf{x}$ is delayed by one sample to get $\mathbf{x}_{\text{delay}}$, the k th element of which satisfies $\mathbf{x}_{\text{delay}}(k) = \mathbf{x}(k-1)$. The differential preamble sequence $\mathbf{y}$ is obtained by the Hadamard product of $\mathbf{x}$ and $\mathbf{x}_{\text{delay}}$:

$$\begin{aligned} \mathbf{y} &= \mathbf{x} \circ \bar{\mathbf{x}}_{\text{delay}}, \\ \mathbf{y}(k) &= \mathbf{x}(k) \bar{\mathbf{x}}_{\text{delay}}(k) = \mathbf{p}(k) \bar{\mathbf{p}}(k-1) e^{j2\pi \Delta f \tau}. \end{aligned}$$

Now the length of sequence $\mathbf{y}$ is $L-1$ and the differential preamble sequence has a constant phase offset $2\pi \Delta f \tau$ compared to the differential reference preamble sequence

$$\mathbf{r} = \mathbf{p} \circ \bar{\mathbf{p}}_{\text{delay}}. \quad (5)$$

It is assumed that the differential sequences also have good correlation properties, as the underlying PN sequence has good correlation property. Packet detection is finally performed by cross correlation between $\mathbf{y}$ and $\mathbf{r}$,

$$C^{\text{DD}}(k) = \sum_{m=0}^{L-2} \mathbf{r}(m) \mathbf{y}(k+m), \quad (6)$$

where the superscript DD is short for differential detection. In (6), with a constant phase shift $2\pi \Delta f \tau$ between $\mathbf{y}(k+m)$ and $\mathbf{r}(m)$, the absolute value of the correlation will not change or decrease, thus outperforming the non-differential algorithm when frequency offset exists.

$$M^{\text{DD}}(k) = \frac{|C^{\text{DD}}(k)|^2}{\|\mathbf{r}\|^2 \|\mathbf{y}\|^2}, \quad (7)$$

$$M_{\text{appr}}^{\text{DD}}(k) = \frac{|C^{\text{DD}}(k)|^2}{\|\mathbf{r}\|^2 \mathbb{E}[\|\mathbf{y}\|^2]}. \quad (8)$$

The differential sequences $\mathbf{r}$ and $\mathbf{y}$ are also normalized for detection metric calculation, which makes the result insensitive to the signal power.

IV. ANALYSIS

In this section, we compare the non-differential algorithm and the differential algorithm under AWGN with and without frequency offset. For each algorithm, the detection metric M is calculated for two cases: when the captured sequence is noise and when the received preamble samples are perfectly aligned with the reference samples. Due to the fact that in a limited-mobility environment (coherence time $\gg$ preamble duration), the SNR is roughly constant during the preamble, AWGN analysis is realistic in industrial fading environments. Moreover, in the following section we have tested the proposed algorithms in a real factory environment, where fading, shadowing, and other channel impairments are present, and the results of these experiments confirm the good reliability of the presented detection schemes in real propagation environments.

A. Non-differential Detection Algorithm

1) *Detection metric in noise:* During the idle time, the captured samples are just noise, that is $\mathbf{x} = \mathbf{n}$. The mean and variance of the independent real and imaginary parts of $\mathbf{n}$ are

$$\mathbb{E}[\mathbf{n}_I(k)] = \mathbb{E}[\mathbf{n}_Q(k)] = 0, \quad (9)$$

$$\mathbb{E}[\mathbf{n}_I^2(k)] = \mathbb{E}[\mathbf{n}_Q^2(k)] = \sigma_n^2, \quad (10)$$

where the subscripts I and Q represent the real and imaginary component of the samples.

The correlation between the reference sequence and the received noise sequence is

$$\begin{aligned} C^{\text{ND}}(k_n) &= (\mathbf{p}_I + j\mathbf{p}_Q)^H (\mathbf{n}_I + j\mathbf{n}_Q) \\ &= \sum_{m=0}^{L-1} \mathbf{p}_I(m) \mathbf{n}_I(k_n + m) + \mathbf{p}_Q(m) \mathbf{n}_Q(k_n + m) \\ &\quad + j[\mathbf{p}_I(m) \mathbf{n}_Q(k_n + m) - \mathbf{p}_Q(m) \mathbf{n}_I(k_n + m)], \end{aligned} \quad (11)$$

where k_n represents the start sample index of a sequence of noise. Since the real and imaginary parts of $C^{\text{ND}}(k_n)$ are independent sums of Gaussian noise variables, each of which has zero mean and variance $\|\mathbf{p}\|^2 \sigma_n^2$, $|C^{\text{ND}}(k_n)|^2$ follows a chi-square distribution with 2 degrees of freedom,

$$|C^{\text{ND}}(k_n)|^2 = \|\mathbf{p}\|^2 \sigma_n^2 \chi^2, \quad (12)$$

where χ^2 is a central chi-squared distributed random variable.

When $\mathbf{x} = \mathbf{n}$, simple algebra gives that

$$M_{\text{appr}}^{\text{ND}}(k_n) = \frac{|C^{\text{ND}}(k_n)|^2}{\|\mathbf{p}\|^2 \mathbb{E}[\|\mathbf{n}\|^2]} = \frac{1}{2L} \chi^2, \quad (13)$$

$$\mathbb{E}[M_{\text{appr}}^{\text{ND}}(k_n)] = \frac{1}{L}, \quad (14)$$

The distribution of $M_{\text{appr}}^{\text{ND}}(k_n)$ only varies with the preamble length L , and is independent from the absolute noise power, due to the fact that the detection metric is normalized.

2) *Detection metric with received preamble symbol:* When the preamble symbol is present, $\mathbf{x} = \alpha \mathbf{p} + \mathbf{n}$, where α represents the signal attenuation. Denote $\sigma_p^2 = \|\mathbf{p}\|^2 / (2L)$, then,

$$\text{SNR} = \frac{\alpha^2 \|\mathbf{p}\|^2}{2L \sigma_n^2} = \frac{\alpha^2 \sigma_p^2}{\sigma_n^2}. \quad (15)$$

The correlation between the received samples and the reference preamble sequence can be calculated as

$$\begin{aligned} C^{\text{ND}}(k_a) &= (\mathbf{p}_I + j\mathbf{p}_Q)^H (\mathbf{p}_I + \mathbf{n}_I + j\mathbf{p}_Q + j\mathbf{n}_Q) \\ &= (\mathbf{p}_I + j\mathbf{p}_Q)^H (\alpha \mathbf{p}_I + j\alpha \mathbf{p}_Q) \\ &\quad + \sum_{m=0}^{L-1} \{ \mathbf{p}_I(m) \mathbf{n}_I(k_a + m) + \mathbf{p}_Q(m) \mathbf{n}_Q(k_a + m) \\ &\quad + j[\mathbf{p}_I(m) \mathbf{n}_Q(k_a + m) - \mathbf{p}_Q(m) \mathbf{n}_I(k_a + m)] \}, \end{aligned} \quad (16)$$

where k_a represents the received preamble sequence that is aligned with the reference sequence at sample index k_a . Similarly with the calculation of $M_{\text{appr}}^{\text{ND}}(k_n)$, the detection metric when the preamble is present is

$$M_{\text{appr}}^{\text{ND}}(k_a) = \frac{|C^{\text{ND}}(k_a)|^2}{\|\mathbf{p}\|^2 \mathbb{E}[\|\alpha \mathbf{p} + \mathbf{n}\|^2]} = \frac{\sigma_n^2}{2L(\alpha^2 \sigma_p^2 + \sigma_n^2)} \chi^2, \quad (17)$$

where χ^2 here is a non-central chi-squared distributed random variable, as the real part of $C^{\text{ND}}(k_a)$ has a nonzero mean. The distribution of $M_{\text{appr}}^{\text{ND}}(k_a)$ is affected by the preamble length L and SNR.

The expected value of $M_{\text{appr}}^{\text{ND}}(k_a)$ is

$$\mathbb{E}[M_{\text{appr}}^{\text{ND}}(k_a)] = \frac{L \text{SNR} + 1}{L(\text{SNR} + 1)}. \quad (18)$$

The case SNR=0 reduces to the noise-only case of (14).

B. Differential Detection Algorithm

1) *Detection metric in noise:* When the captured samples are noise, $\mathbf{x} = \mathbf{n}$, and $\mathbf{y} = (\mathbf{n} \circ \bar{\mathbf{n}}_{\text{delay}})$. With the reference preamble sequence $\mathbf{r}$ defined as in (5), and assuming that $\mathbf{p}$ has ideal correlation properties, we have $\|\mathbf{r}\|^2 = 4(L-1)\sigma_p^4$.

The correlation between $\mathbf{y}$ and $\mathbf{r}$ is

$$\begin{aligned} C^{\text{DD}}(k_n) &= \mathbf{r}^H (\mathbf{n} \circ \bar{\mathbf{n}}_{\text{delay}}) \\ &= \sum_{m=0}^{L-2} (\mathbf{r}_I(m) - j\mathbf{r}_Q(m)) \cdot [(\mathbf{n}_I(k_n + m) + j\mathbf{n}_Q(k_n + m)) \\ &\quad \cdot (\mathbf{n}_I(k_n + m - 1) - j\mathbf{n}_Q(k_n + m - 1))]. \end{aligned} \quad (19)$$

Assuming white noise $\mathbf{n}$, the noise product terms in (19) are dependent only on the adjacent terms, and are hence independent random variables with $m = 1$ according to the definition in [31]. Real and imaginary parts of $C^{\text{DD}}(k_n)$ are uncorrelated random variables with zero-mean and variance $2\|\mathbf{r}\|^2 \sigma_n^4$. By Theorem 2 in [31], they are approximately Gaussian distributed. Then

$$M_{\text{appr}}^{\text{DD}}(k_n) = \frac{|C^{\text{DD}}(k_n)|^2}{\|\mathbf{r}\|^2 \mathbb{E}[\|\mathbf{y}\|^2]} = \frac{1}{2(L-1)} \chi^2, \quad (20)$$

$$\mathbb{E}[M_{\text{appr}}^{\text{DD}}(k_n)] = \frac{1}{L-1}. \quad (21)$$

The statistical property of the detection metric of noise for the differential detection algorithm is similar to the non-differential algorithm.

2) *Detection metric with received preamble symbol:* When the preamble symbol is present $\mathbf{x} = \alpha \mathbf{p} + \mathbf{n}$, and $\mathbf{y} = (\alpha \mathbf{p} + \mathbf{n}) \circ (\alpha \bar{\mathbf{p}}_{\text{delay}} + \bar{\mathbf{n}}_{\text{delay}})$.

$$\mathbb{E}[\|\mathbf{y}\|^2] = 4(L-1)(\alpha^2 \sigma_p^2 + \sigma_n^2)^2 \quad (22)$$

The correlation between $\mathbf{y}$ and $\mathbf{r}$ is

$$\begin{aligned} C^{\text{DD}}(k_a) &= \mathbf{r}^H [(\alpha \mathbf{p} + \mathbf{n}) \circ (\alpha \bar{\mathbf{p}}_{\text{delay}} + \bar{\mathbf{n}}_{\text{delay}})] \\ &= \sum_{m=0}^{L-2} (\mathbf{r}_I(m) - j\mathbf{r}_Q(m)) \cdot [(\alpha \mathbf{p}_I(k_a + m) \\ &\quad + j\alpha \mathbf{p}_Q(k_a + m) + \mathbf{n}_I(k_a + m) + j\mathbf{n}_Q(k_a + m)) \\ &\quad \cdot (\alpha \mathbf{p}_I(k_a + m - 1) - j\alpha \mathbf{p}_Q(k_a + m - 1) \\ &\quad + \mathbf{n}_I(k_a + m - 1) - j\mathbf{n}_Q(k_a + m - 1))]. \end{aligned} \quad (23)$$

Similarly with the analysis of $M_{\text{appr}}^{\text{DD}}(k_n)$, the detection metric when preamble is present follows non-central chi-square distribution

$$\begin{aligned} M_{\text{appr}}^{\text{DD}}(k_a) &= \frac{|C^{\text{DD}}(k_a)|^2}{\|\mathbf{r}\|^2 \mathbb{E}[\|\mathbf{y}\|^2]} \\ &= \frac{1}{2(L-1)(\text{SNR} + 1)^2} \chi^2, \end{aligned} \quad (24)$$

$$\mathbb{E}[M_{\text{appr}}^{\text{DD}}(k_a)] = \frac{\text{SNR}^2}{(1 + \text{SNR})^2} + \frac{1}{(1 + \text{SNR})^2(L-1)}. \quad (25)$$

The distribution of the detection metric with received preamble for the differential algorithm is similar to the non-differential algorithm.

TABLE III
PREAMBLE GENERATION PARAMETERS FOR SIMULATION

N_{FFT}	32
N_{CP}	2
PN generator polynomial	[5 4 0]
Modulation	BPSK

Fig. 3. Histogram of the detection metric of non-differential algorithm and PDF of its approximation when SNR = 6 dB.

Fig. 4. Histogram of the detection metric of differential algorithm and PDF of its approximation when SNR = 6 dB.

C. Simulation Results

As we can not measure accurately the SNR with our available experimental instruments, we first use simulations to validate the accuracy of the theoretical results with approximation. In this subsection, simulation with random noise is used to present how the false alarm probability (Pr_{FA}) and missed detection probability (Pr_{MD}) vary with threshold and received SNR. Simulation is used to obtain these probabilities, while analytical results are obtained from the theoretical distributions of the approximated metrics (3) and (8). The results are plotted in the same figures. The simulation parameters are chosen to be consistent with the experimental setup based on SDR in Section V. The preamble power is fixed to be 1, and the noise power changes according to the SNR value. The length of the preamble symbol L is 34 with $N_{\text{FFT}} = 32$ and $N_{\text{CP}} = 2$. The parameters of the PN sequence generation are listed in Tab. III.

To validate the accuracy of the approximations (3) and (8) of (2) and (7) respectively, we calculate the detection metrics (2) and (7) in the two cases of noise and preamble

Fig. 5. False alarm probability, missed detection probability and detection error rate of non-differential detection algorithm. The simulation results of the exact algorithms are plotted in solid lines, while the approximated theoretical results are plotted in dashed lines.

Fig. 6. False alarm probability, missed detection probability and detection error rate of differential detection algorithm. The simulation results of the exact algorithms are plotted in solid lines, and the approximated theoretical results are plotted in dashed lines.

symbol with simulations, and present the histograms in Fig. 3 and Fig. 4. The theoretical probability density functions of the approximations (3) and (8) are also plotted in the same figure for comparison. For the detection metrics in noise, the theoretical distribution of approximated metrics (3) and (8) are only coarse approximations of the true distributions of (2) and (7) respectively. If we transform the distributions to calculate Pr_{MD} , when the threshold is set around 0.5 in Fig. 3 and Fig. 4, Pr_{MD} of the non-differential algorithm is less than its theoretical approximation, while the differential algorithm has a larger Pr_{MD} than that of its theoretical approximation. Comparing the two figures, when the preamble is present and the SNR is the same, the probability distribution of the non-differential detection algorithm concentrates around 0.82, while the one of the differential algorithm is concentrates around 0.68, which illustrates the decrease of the correlation caused by the differential transformation. It should also be noted that, despite the range of the detection metric of the two algorithms is within 0-1, the range of the approximated detection metrics is no longer restricted to be less than 1.

Pr_{FA} and Pr_{MD} of (2) for the non-differential algorithm are

plotted in solid lines in Fig. 5, and approximated probabilities from (13) and (17) are plotted in dashed lines. It is seen that the exact and the approximated probabilities share the same trend with the change of SNR. Pr_{FA} decreases with increasing threshold, but is not affected by the absolute noise power due to the normalization. Pr_{MD} , instead, increases with increasing threshold but decreases with rising SNR when fixing the threshold.

The false alarms can be detected by cyclic redundancy check later in the decoding process, and, when this happens, the whole packet will be discarded to guarantee fast detection in the real-time communication. Thus, if the false alarm occurs less than L samples before the real starting sample of the preamble, it will cause a missed detection. We hence define the evaluation criteria to be detection error rate (DER),

$$\text{DER} = \text{Pr}_{\text{MD}} + \frac{T_{\text{preamble}}}{T_{\text{cycle}}} \text{Pr}_{\text{FA}}, \quad (26)$$

where T_{preamble} and T_{cycle} represent the duration of the preamble symbol and the TDMA cycle duration respectively. The weighted Pr_{FA} represent the probability that a false alarm will result in a missed detection. $1/50$ is chosen for the weight in the simulation, which represents the case when the packet duration is around 5 times the preamble duration, and the TDMA cycle is around 10 times the packet duration.

The DER of the non-differential algorithm is plotted in the last subfigure in Fig. 5. As 10^{-6} DER is set as the baseline requirement, for the non-differential algorithm the optimal threshold is around 0.4, which can guarantee the weighted Pr_{FA} is smaller than 10^{-6} . From the DER subfigure, the minimum required SNR to satisfy the DER requirement is 4 dB. Fig. 6 shows the corresponding probabilities of the differential detection algorithm, and the trend of each probability is the same as the non-differential algorithm. To achieve a DER smaller than 10^{-6} , the optimal threshold is at around 0.4, and the minimum required SNR is 8 dB. It should be noted that the minimum required SNRs of both algorithms are higher than the SNR needed to guarantee a low bit error rate for the decoding with low order modulation. Thus the minimum requirements to guarantee high packet detection probability should be well studied when high reliability is needed at the receiver side.

Pr_{FA} , Pr_{MD} , and DER against frequency offset of the two algorithms are shown in Fig. 7 with SNR fixed at 10 dB. The frequency offset is represented in terms of the phase change during one sample duration $2\pi k\Delta f\tau$. Pr_{FA} does not vary with the frequency offset, as the false alarms are caused by the Gaussian noise. It can be observed that the non-differential algorithm is not robust to frequency offset. In Fig. 7, Pr_{MD} of non-differential algorithm increases with the threshold and frequency offset, as the frequency offset causes the detection metric to decrease when the preamble is present. From the DER subfigure, the non-differential algorithm can tolerate frequency corresponding to 0.02π phase change during one sample duration, and the optimal threshold region is around 0.4. The differential algorithm is instead designed to be robust against frequency offset and indeed, from Fig. 8, Pr_{MD} does not decrease with the frequency offset. The DER

Fig. 7. False alarm probability, missed detection probability and detection error rate of non-differential detection algorithm against frequency offset.

Fig. 8. False alarm probability, missed detection probability and detection error rate of differential detection algorithm against frequency offset.

of the differential algorithm can satisfy the requirement over a wide frequency offset range from 0.008π to 0.8π phase change during one sample duration. Thus the differential detection algorithm is very robust against frequency offset when the minimum SNR requirement is satisfied.

The simulation results with no approximation are consistent with the approximated theoretical analysis Subsection IV-A and IV-B.

D. Preamble duration comparison between WirelessHP and other protocols

In this section so far the reliability of the proposed preamble structure and detection methods have been evaluated, showing good results. In order to understand the advantage of the proposed preamble in terms of latency, in this subsection we first compare the structure and duration of our preamble with those of several PHY layers proposed in IEEE 802.11, which represents the base for different industrial wireless technologies [24], [26], then we compare with three industrial wireless protocols using cyclic communication including WirelessHART [21], WISA [25], and WIA-FA [26].

TABLE IV
PREAMBLE DURATION COMPARISON BETWEEN WIRELESSHP AND IEEE 802.11 PROTOCOLS.

	IEEE 802.11a/g	IEEE 802.11n	IEEE 802.11ac	WirelessHP	
Preamble symbol No.	5	7	10	1	
Bandwidth	20 MHz	80 MHz	80 MHz	20 MHz	80 MHz
FFT size	64	256	256	32	32
Preamble duration (μ s)	16	22.4	32	2	0.8

TABLE V
COMPARISON OF WIRELESSHP PHY PERFORMANCE WITH OTHER INDUSTRIAL WIRELESS PROTOCOLS ASSUMING A 100-BIT PSDU.

	WirelessHART	WISA	WIA-FA	WirelessHP
Underlying standard	IEEE 802.15.4	IEEE 802.15.1	16 IEEE 802.11	Proprietary
Preamble duration	160 μ s	45 μ s	16 μ s	1.2 μ s
Data rate	250 kbps	1 Mbps	54 Mbps	30 Mbps
Modulation	DSSS (QPSK)	GFSK	OFDM (64QAM)	OFDM (64QAM)
Code rate	No coding	No coding	3/4	3/4
Packet transmission time	592 μ s	168 μ s	24 μ s	4.8 μ s
Normalized preamble ratio	0.27	0.268	0.667	0.25

Table IV presents the preamble duration comparison between our WirelessHP scheme and IEEE 802.11 protocols. It can be seen that the different IEEE 802.11 PHY versions present different number of preamble symbols, bandwidth and FFT size, which result in specific durations. Despite being the oldest and the one with the narrowest bandwidth, the IEEE 802.11a/g preamble is the shortest one, with a duration of 16 μ s, while the most recent IEEE 802.11ac takes 32 μ s. Comparing these numbers with the requirements in Tab. I, it can be seen that the preamble durations alone are much longer than the targeted scheduling unit. Considering, instead, the proposed WirelessHP preamble structure, the number of symbols is fixed to 1 and the FFT size is optimized along with the payload size, modulation, coding, transmission bandwidth (the interested readers can refer to [27] for details on the optimization procedure). For example, considering 100 bit payload size, 5/6 coding rate, QPSK modulation, and 400 ns for CP length, the preamble durations are 2 μ s and 0.8 μ s with 20 MHz and 80 MHz bandwidth respectively. It can be observed that both cases greatly outperform all the IEEE 802.11 PHYs in terms of preamble duration and, hence, of overall latency.

The comparison between WirelessHP and IEEE 802.11 is not completely fair, as the latter is not optimized for cyclic industrial communications. Hence, in Table V, the PHY latency performance of WirelessHP scheme are compared with that of three industrial wireless protocols, namely WirelessHART, WISA, and WIA-FA, assuming a 100-bit PHY Service Data Unit (PSDU). The three protocols all adopt a TDMA-based superframe for cyclic industrial communication. WirelessHART is based on 802.15.4. Its PHY uses a direct sequence spread spectrum (DSSS) scheme with offset-QPSK modulation and no channel coding. The 32-bit preamble and 8-bit start-of-packet delimiter are used for packet synchronization and the packet size with 100-bit PSDU is 148 bits (including a 8-bit PHY header). Considering the data rate of 250 kb/s, the durations of the preamble and the entire packet are 160 μ s and 592 μ s respectively. WISA is based on the 802.15.1 standard, with GFSK modulation, no channel coding and 1 Mbps data

rate. A 2.048 ms superframe is divided into 32 uplink slots, and the duration of each slot is 64 μ s. Each uplink slot carries 56 bits, divided into 15 bits for the preamble, and a 41 bits PSDU. It takes 3 uplink slots to transmit a 100-bit PSDU, so that the total preamble duration and packet transmission time are 45 μ s and 168 μ s respectively. WIA-FA is based on the IEEE 802.11-2012 standard and adopts the OFDM PHY, with a preamble duration of 16 μ s and a 20 MHz bandwidth. Though a 100-bit PSDU can fit in one OFDM symbol (4 μ s) by using a 64QAM modulation with 3/4 code rate, the total packet duration is 24 μ s, once the preamble and one-symbol signal field are added. Considering our WirelessHP scheme with the same modulation and coding as WIA-FA and a 100-bit PSDU, the optimal FFT size is 16, resulting in 3 data symbols to transmit the packet. Considering a 400 ns cyclic prefix duration and 20 MHz bandwidth, each OFDM symbol is 1.2 μ s long, and the packet transmission time is 4.8 μ s, with 1 preamble symbol and 3 data symbols.

The different PHY implementations are compared in terms of absolute preamble duration and normalized preamble ratio, defined as the preamble duration divided by the packet transmission time. It can be observed that WirelessHP PHY provides by far the shortest preamble and also the most efficient ratio between preamble and packet duration. In detail, when compared with WirelessHART and WISA, the normalized preamble ratio is similar (but slightly lower for WirelessHP), but the total preamble and packet duration are much lower, since those two standards have quite low data rates. The comparison with WIA-FA is more fair, since it is a high data rate standard which also uses OFDM, but WirelessHP is much more efficient when the PSDU is as short as 100 bits, with a normalized preamble ratio of 0.25 against the 2/3 of WIA-FA. This leads to a much shorter duration of the whole packet (5 times shorter in WirelessHP).

V. EXPERIMENTAL RESULTS

In this section, the detection performance of the differential and non-differential detection algorithms are compared by real-world experiments for different transmission distance and

Fig. 9. Experimental setup based on USRP X310 in an industrial motor lab.

frequency offset. We also investigate how the transmission prediction discussed in Subsection III-B can help reducing the detected false alarms and how the presence of a moving obstacle affects the DER performance.

A. Experimental setup

The experimental setup is shown in Fig. 9: two Ettus Universal Software Radio Peripheral (USRP) model X310 (a transmitter and a receiver) are placed in an industrial site with running motors. Although the two radios are in line-of-sight, there are metal pipes up in the ceilings that can act as reflectors, providing a rich fading environment. The transmitting USRP is placed at a higher and fixed position, while the receiving USRP is placed on a moving trolley to change the communication distance to the transmitter, with a step being 0.5 m. Each USRP is equipped with an SBX-40 daughterboard that operates in the 0.4-4.4 GHz range and supports a maximum 40 MHz bandwidth. Each radio is connected to a PC through a Gigabit Ethernet cable, and the PC performs processing of baseband samples in near real time. Finally, an Anritsu MS2720T spectrum analyzer is used to monitor the received signal.

In our experiments, the central frequency is set to 866.5 MHz, and the frequency accuracy is 2.5 ppm. The frequency band has been chosen among the license-exempt ones to avoid the interference of co-located WLANs working at 2.4 GHz (the 5 GHz band was not available with the employed RF boards). The bandwidth is set to 5 MHz due to the limitation of the operational ability by the USRP. In the WirelessHP PHY, the payload bits are mapped into each data subcarrier, together with some padding zeros if the number of data subcarriers is higher than that necessary for the payload bits. The FFT size is derived through an optimization procedure [27], which aims at minimizing the packet transmission time (defined as the sum of the duration of OFDM symbols for the payload and the single OFDM

Fig. 10. Detection error rate performance of differential and non-differential algorithms against distance.

symbol for the preamble symbol), given the payload size, bandwidth, modulation order, code rate and a fixed value of non-data subcarriers (for guard bandwidth, pilot symbols and DC offset compensation). For this paper, a payload size of 104 bits, convolutional channel coding with 5/6 rate and three low-order modulation (BPSK, QPSK, and 8PSK) were chosen, while the number of non-data subcarriers was fixed to 11. The corresponding optimal FFT size is 32 with a CP length of 2. Under this configuration, the duration of one preamble symbol is 6.8 μ s, which only accounts for 1/10 of the preamble durations in IEEE 802.11 a/g (when configured with a comparable bandwidth). The number of payload symbols, instead, corresponds to 6, 3 and 2 for BPSK, QPSK and 8PSK, with a corresponding total packet duration of 47.6, 27.2 and 20.4 μ s respectively. It is worth to underline that this paper only investigates preamble detection performance, and the preamble is always modulated with BPSK, thus the change of the modulation of the payload only affects the duration of the packet. At the receiver side, the parameters are set according to the transmitter side, and the known preamble sequence is stored locally for packet detection. According to the simulation results in Subsection IV-C, the detection threshold is set to 0.4 for both the non-differential and differential detection algorithm, to guarantee that the weighted P_{rFA} is less than 10^{-6} .

B. Comparison between the non-differential and differential algorithms

To validate the DER performance of the non-differential and differential detection algorithms at different SNRs, the distance between the transmitter and receiver is changed. The transmission power is fixed at 9 dBm, and there is no artificial offset between the central frequency at the transmitter and receiver side. For both algorithms, at every distance step, 10^8 packets are captured to calculate the DER.

Fig. 10 shows the DER performance of the two algorithms, and longer distance represents smaller SNR in the figure. When the distance is shorter than 20 m, there is no detection error captured for both algorithms, while the DER grows rapidly when the distance grows further. This behaviour is consistent with the theoretical results in Fig. 5 and 6, as the decrease in SNR leads to the decrease in the detection metric

Fig. 11. Performance of differential and non-differential algorithms against frequency offset.

and ultimately missed detections. The DER of differential detection algorithm grows faster than the non-differential algorithm when the distance exceeds 20 m, as the minimum required SNR of the differential algorithm to guarantee 10^{-6} DER is higher than that of the non-differential detection algorithm. Note that the distance does not give an exact quantification of the detection algorithms performance, but can still be considered to validate the results of the theoretical analysis and simulation. As we have just one preamble symbol, the PN sequence is shorter compared to that of the long preambles, the correlation property at low SNR degrades, and coverage distance will possibly decrease. However the coverage distance is not the primary concern as most of the critical applications considered in this paper are less sensitive to distance. This preliminary information also suggests that the detection performance in terms of communication range is comparable with WLAN, which is around 20 m for the indoor case with transmitter power 9 dBm and 5 MHz bandwidth.

In a following experiment, we fix the distance between the transmitter and receiver to 10 m, and change the central frequency at the transmitter side to artificially generate a frequency offset compared to the central frequency at the receiver side. From Fig. 11, the DER of the non-differential detection algorithm grows rapidly from ± 70 ppm of the central frequency at the receiver side, which corresponds to a phase 0.0243π phase change during one sample duration, while the differential detection algorithm starts to fail at around ± 1200 ppm, which corresponds to a phase 0.4160π phase change during one sample duration. This large difference is due to the fact that the non-differential algorithm is not robust to the frequency offset, and larger frequency offsets will decrease the similarity between the local known preamble sequence and the received samples and also the detection metric value. Conversely, the differential algorithm is designed to fight the frequency offset by performing the differentiation between the neighbouring samples.

From the two experimental results, it can be concluded that differential detection algorithm is slightly inferior to the non-differential algorithm against distance. However, when frequency offsets exists, the differential algorithm outperforms significantly the non-differential algorithm with suitable SNR. The experimental results are consistent with the simulation

results and the theoretical analysis.

C. Comparison between detection algorithms with and without transmission prediction

The transmission prediction mechanism described in Subsection III-B helps to reduce the false alarms and the computation at the receiver side. The detected false alarm probability $\Pr_{\text{FA-detected}}$ can be calculated as

$$\Pr_{\text{FA-detected}} = \frac{T_{\text{on}}}{T_{\text{cycle}}} \cdot \Pr_{\text{FA}}, \quad (27)$$

where T_{on} is the time when the detection is turned on, and it satisfies $T_{\text{preamble}} \leq T_{\text{on}} \leq T_{\text{cycle}}$.

As in Fig. 2, when transmission prediction is enabled, after the packet has been detected the detector will be closed until the predicted start of the next packet. In this case, T_{on} is slightly larger than T_{preamble} , and $\Pr_{\text{FA-detected}}$ is reduced proportionally. If there is no transmission prediction, $T_{\text{on}} = T_{\text{cycle}}$, and, in this case, $\Pr_{\text{FA-detected}} = \Pr_{\text{FA}}$. When there is an interfering transmitter, P_{FA} is related to how similar the preamble symbol from the interferer is to that from the transmitter, and to the periodicity of the interfering signal.

To capture the false alarm event, we artificially design an extreme scenario in which another USRP is sending packets with the same preamble pattern as the designated transmitter, acting as an interference source. The interferer is sending at a much lower power and the time interval between two transmitted packets is random and much longer than the cycle time of the designated transmitter. The power of the captured samples are plotted in Fig. 12. It can be seen that the power of the interference is around 20 dB lower than the transmitted signal. However, when the transmission prediction is disabled, the interfering signal may still be detected, causing false alarms. These alarms can instead be avoided if prediction is on, and this mechanism works on top of both the differential and non-differential algorithm, as it does not affect the algorithms themselves, but only controls when to perform the detection.

The detected false alarm probabilities of the combinations of each of the two algorithms and whether the transmission prediction is applied are listed in Table VI. It is clear to see that, with transmission prediction, around 1% false alarms from the interference are avoided. It is worth to remember that the false alarm probability is related with the periodicity of the interferer and the similarity of the interfering preamble with the local preamble reference, and this experiment only allows to conclude that the prediction mechanism has the potential to reduce the detected false alarm and computation at the receiver.

The transmission prediction is applied when the traffic is deterministic and periodic. In case of random and mixed traffic, the packet detection must be always on, and when the SNR is low, some samples with patterns similar to the preamble sequence may be detected as the start of a new packet, causing a false alarm. However, the negative effect of false alarms can be considered when designing the whole system, so that they are not fatal to our system, as they can be detected later in the decoding phase.

Fig. 12. Received samples when the interfering USRP is working.

TABLE VI
Pr_{FA-detected} OF PREDICTIVE AND NON-PREDICTIVE DETECTION ALGORITHMS AGAINST INTERFERENCE.

	Predict	Non-predict
Differential	0	0.0095
Non-differential	0	0.0098

Fig. 13. Experimental setup with a moving obstacle.

Fig. 14. The obstacle blocks the transmission link at around $T = 3$ s. (a) and (b) characterize the DER performance of differential and non-differential with moving obstacle.

D. The influence of a moving obstacle

In industrial sites, it is common to have robots and/or transporting vehicles moving. To reproduce these scenarios,

a new experiment is devised where an available metal object is used to act as a moving obstacle. The test setup is shown in Fig. 14, which is arranged in a more controllable way to block the line-of-sight path of the transmitter and receiver. The obstacle is made of metal with size 0.5×0.5 m² and moves with pedestrian speed 2 m/s, thus the time in which the direct link between the transmitter and receiver is blocked is around 0.25 s. Observing by the spectrum analyzer, when the obstacle remains static, it causes around 10 dB attenuation. Besides the spectrum analyzer, the power of the received signal can also be reflected by the initialized receiving gain by the AGC. When the receiving gain is far from the maximum value, the attenuation caused by the static or moving obstacle will not result in any missed detections. However, when the receiving gain reaches or stays around the maximum value, moving the obstacle will cause missed detection when the direct link between the transmitter and receiver is blocked. The result is shown in Fig. 14. The time resolution is in the x-axis in Fig. 14 is 0.1 s and a packet is sent every 200 μ s, thus each marker corresponds to 500 packets. From the figure, for both the non-differential and differential detection algorithms, the moving obstacle causes the DER to rise for a duration of 0.2 s. Thus, if there are obstacles moving in the workshop, a sufficiently high transmission power is the key to guarantee good detection performance.

VI. CONCLUSION AND FUTURE WORK

A short PHY layer preamble composed of just one OFDM symbol was proposed for the URLLC critical industrial control applications requiring ultra low latency, and corresponding techniques for packet detection of OFDM signals were discussed and analyzed. The evaluation included theoretical analyses, numerical simulations and experimental validation via Universal Software Radio Peripheral (USRP) devices. The proposed preamble structure allowed to reduce the duration of the preamble of around 1/10 with respect to IEEE 802.11 a/g having comparable bandwidth. A differential detection algorithm was applied which, according to theoretical analysis, is robust to a wide range of carrier frequency offsets that cause a phase offset as large as 0.8π , and this came with the price of around 4 dB higher minimum SNR than the non-differential detection algorithm to achieve 10^{-6} detection error rate. As a further enhancement, which exploits the deterministic traffic pattern, transmission prediction can be used to reduce the computation for packet detection and improve the detection performance in the presence of interference.

Experiments in a real factory-like environment showed that the proposed preamble guarantees perfect accuracy up to 20 m range and, when the differential detection is employed, frequency offsets up to ± 1200 ppm can be tolerated. The transmission prediction mechanism allows to avoid false alarms caused by non-aligned interferers using the same preamble. Finally, for industrial sites with moving obstacles, to guarantee good detection performance, the transmission power should be increased compared to the minimum value with respect to the line-of-sight link, to compensate the attenuation caused by the moving obstacles.

There are some limitations in the experiments. Due to the small buffer size in the USRP devices, they can only capture samples up to a maximum 20 s duration for a single experiment. During this short duration, the channel is considered static, and the receiver gain is fixed after being set by automatic gain control (AGC) at the initialization phase. In the future, upgraded hardware is expected to run longer and to process samples in real time. In this case, the AGC should slowly tune the receiving gain along the time and the transmission prediction could be combined to the AGC, as it can help avoid sudden receiver gain fluctuations caused by counting the signal power from the false alarms. For the preamble design, the Zadoff-Chu sequence is known to have better auto-correlation properties than PN sequence [32], and we consider to investigate the performance of such sequence as future work. Moreover, whereas this work focuses on physical layer design, higher layer design to achieve low latency and deterministic communications will be the subject of following research. Finally, one of the future goals is to extend the validation of the proposed one-symbol preamble to scenarios characterized by a higher degree of mobility, by exploiting better preamble design, more advanced detection algorithms and cross layer mechanisms.

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