Short-Packet Interleaver against Impulse Interference in Practical Industrial Environments

Ming Zhan, Member, IEEE, Zhibo Pang, Senior Member, IEEE, Dacfey Dzung, Life Member, IEEE, Kan Yu, Member, IEEE, and Ming Xiao, Senior Member, IEEE

Abstract—Impulse interference is an important cause of transmission failure in the industry environments targeted by the Wireless High Performance (WirelessHP). As interleavers are commonly used to improve the reliability on the Orthogonal Frequency Division Multiplexing (OFDM) symbol level for long packet transmission, this paper considers the feasibility of applying short-packet bit interleaving to enhance the impulse/burst interference resisting capability on both OFDM symbol and frame level. Using the Universal Software Radio Peripherals (USRP) and PC hardware platform, the Packet Error Rate (PER) performance of interleaved coded short-packet transmission with Convolutional Codes (CC), Reed-Solomon (RS) codes, and RS+CC concatenated codes are tested and analyzed. The IEEE 1613 standard is applied for impulse interference generation, and extensive PER tests of CC(1/2) and RS(31,21)+CC(1/2) concatenated codes are conducted. We prove the effectiveness of bit interleaved coded short-packet transmission in real factory environments with practical experiments. Moreover, we investigate how PER performance depends on the interleavers, codes and impulse interference power and frequency.

Index Terms—Short packet, Impulse interference, Interleaver, WirelessHP, Universal software radio peripherals, Channel coding, Packet error rate, Industrial environments.

I. INTRODUCTION

OVER the past decade, with the rapid advances in emerging technologies (e.g. information and communication technology, sensors, intelligent robots), the traditional manufacturing industry has been undergoing a digital transformation at a tremendous pace [1]. Some industrial wireless communication standards, such as WirelessHART, WIA-PA and WIA-FA [2]–[4], can match the moderate ms level latency requirement in typical Process Automation (PA) and Factory Automation (FA) applications. However, these standards are not applicable in some critical fields of industrial applications, such as Power Systems Automation (PSA) and Power Electronics Control (PEC), where ultra-high reliability, ultra-low latency and determinism are strictly required [5]–[7]. For transmission of 100 bits short-packet with lower than 10 μs latency, the Wireless High-Performance (WirelessHP) was proposed to meet these stringent requirements [8]. However, among the most common causes of transmission failures in factory environments, impulse interference is a significant impediment to achieving the intended goal [9]. Therefore, the IEEE 1613 standard stipulates that wireless communication systems for control purposes should be designed to resist impulse interference [10]–[12].

In industrial scenarios where WirelessHP is applied, the positions of central controllers, sensors and actuators are usually fixed [8], [13]. However, the wireless channel in industrial environments is significantly different from home or office environments. Human/robot movement, various equipment, other wireless communication systems operating in the same band of frequencies, and electromagnetic radiation from welding arcs make industrial wireless environments much more complicated. In terms of transmission reliability, 10−7 Packet Error Rate (PER) is achievable in factory environments [14]. But the PER performance can be drastically degraded when suffering from severe impulse interference. Unfortunately, impulse interference cannot be eliminated as it comes from the industrial production processes, for example switching on/off of high voltage equipment or from arcs in electric welding. Another source is the communication system, e.g. spurious emissions from the power supply and the ground wire (refer to Section IV-B). To improve impulse interference resisting capability, relocating position of error bits is an effective solution [15]–[17]. For example, the bit or symbol interleaving technique is employed in [18]–[20] and [21] for coded transmission. However, there is an apparent lack of studies conducted in real factory environments. Only some preliminary results are presented in [22], [23]. More importantly, one of the key differences between the WirelessHP system and current industrial wireless communication standards is that the physical layer of the former is specially designed for short-packet transmission (refer to Section II-C). In light of the new physical layer structure, we are motivated to explore the possibility of adapting interleaver to the WirelessHP paradigm.

© 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.
For this purpose, the WirelessHP physical layer protocols were implemented on a Universal Software Radio Peripherals (USRP) hardware platform. Experiments with different parameter combinations of coding schemes, code rates and interleaver types were performed in factory environments. As part of the PER assessment, four interleavers are used: two block interleavers (one for packets, one for symbols), the 3GPP turbo code interleaver, and the S-random interleaver. Different from the conventional technique that the interleaving/deinterleaving process is performed on one Orthogonal Frequency Division Multiplexing (OFDM) symbol for long packets, this research extends interleavers to a wider OFDM frame level for short packets. Referring to the IEEE 1613 standard [11], we generate impulse interference to simulate electromagnetic interference from other devices and analyze the resilience of interleaved coded short-packet transmission. We show that interleavers can improve the PER performance to a certain degree for different coding schemes. To the best of our knowledge, this is the first research on interleaver in the physical layer with a single preamble for packet detection and 100 bits short packet. The contributions of this research are summarized below.

- By practical experiments in real factory environments, we prove that bit interleaved coded transmission is an effective solution to improve the PER performance of WirelessHP transmission subject to impulse interference. Among all the factors in our experiments, the impulse interference power dominates in affecting PER performance, followed by the impulse frequency and interleaver structure. To fully exploit the advantages of interleaver for short-packet transmission, this paper presents the experimental setup and guidance.

- For short-packet coded transmission, we show that there is room for optimization of the interleaver structure and matching coding schemes to enhance impulse interference resisting capability. Under low-energy impulse noise conditions, interleaving on the OFDM symbol level can slightly improve PER performance but is inferior to interleaving on the frame level. We show that better PER performance can be achieved by interleaving the packet bits in a wider frame range. Furthermore, we demonstrate that coding schemes and interleaver structures have different tolerances for the power and frequency of impulse interference. All these suggest further research in this field.

The rest of this paper is organized as follows. Section II gives background knowledge of impulse noise models, OFDM impulse noise cancellation algorithms, WirelessHP and related works on interleaved coded transmission. In Section III, we present the construction of interleavers from a theoretical perspective. The USRP-PC experimental configuration and the generation of impulse interference are detailed in Section IV. PER comparison and performance analysis of interleaved coded short-packet transmission in factory environments are detailed in Section V. At last, conclusions are summarized in Section VI.

II. BACKGROUND KNOWLEDGE AND RELATED WORKS

This section presents the background knowledge and related works. In Section II-A, the most commonly used impulse noise models in wireless communications are briefly introduced, followed by reviewing the models suitable for industrial environments. Then in Section II-B, the OFDM impulse noise cancellation algorithms are detailed. The WirelessHP concept and its data OFDM frame structure in the time/frequency domain are presented in Section II-C, including the latest progress in this field. At last, Section II-D reviews the interleaved coded transmission strategy, along with the short-packet coding schemes.

A. Impulse noise models

The impulse noise phenomenon, which is sequences of impulses with different durations and intensities and individually occurs in random time, is first proposed by Middleton in [24]. Then in [25], the statistical noise models for the man-made and natural impulse noise were developed, among which the most widely used is the Middleton Class A impulse noise model. The source distribution of the impulse noise in this model is a Poisson process with a parameter termed the impulse index. The generated noise samples’ Probability Density Function (PDF) follows the Gaussian distribution. In power line communication systems, the impulse noise effects can also be represented by the Bernoulli-Gauss model [26]. A noise sample is expressed as the sum of a background Additive White Gaussian Noise (AWGN) sample and a Bernoulli process weighted white Gaussian random sample. If the impulse index of the Middleton Class A noise model is sufficiently low, the Bernoulli-Gauss model is considered an accurate approximation of the Middleton Class A noise model [27].

However, wireless channels in industrial scenarios significantly differ from those in home and office environments. Impulse noise in industrial scenarios may be generated from frequently switching operations to the power source, typically non-Gaussian [28]. The shape, amplitude, duration, and arrival time of an impulse are unpredictable, making it complicated to model the PDF [29]. Consequently, new impulse noise models should be employed in industrial environments. In [30], an impulse can be identified if the amplitude or power of the received signal is higher than a predefined threshold. In [31] and [32], the periodic impulsive noise model is introduced with a shape similar to a damped sinusoid. To evaluate the residual error rate of a safety-critical communication system in the worst industrial environments, [33] stipulates 5 kHz and 100 kHz impulse for testing. In considering the WirelessHP targeted industrial environments, the periodic Surge Withstand Capability (SWC) test required by the IEEE 1613 standard [10]–[12] is adopted for this research, with the impulse frequency ranging from 50 kHz to 700 kHz.

B. OFDM impulse noise cancellation algorithms

OFDM is a high-speed communication technology where data bits are modulated on a number of subcarriers. Considering impulse noise has a very short duration, and the
spectral components are spread over all subcarriers, the long OFDM symbol is less sensitive to the deleterious effect of impulse noise. However, if the impulse noise energy exceeds a certain threshold, the OFDM system performance may be seriously degraded [26], [34]. For the purpose of improved PER performance, impulse noise cancellation algorithms are effective solutions in a bursty channel.

In [30] and [35], algorithms were proposed to estimate the impulse shape, and the redundancy in the guard subcarriers is used to recalculate the impulse noise corrupted samples. In [36], the authors proposed representing the Reed-Solomon (RS) codes with filterbank, and the OFDM modulation is merged to form an improved RS-OFDM scheme for impulse noise mitigation. The work in [37] proposed using pilot subcarriers to cancel the impulse noise. Then this approach is enhanced for time-frequency selective channels [38]. In [34] and [39], the blanking and clipping nonlinearities were proposed to compress impulse noise. In the blanking nonlinearity algorithm, an impulse is detected if the amplitude exceeds a threshold, and the impulse noise is deleted by replacing the sample value with zero. This is different from the clipping nonlinearity algorithm, where the impulse noise is removed by amplitude truncation. Lately, an optimal threshold selection algorithm has been addressed [40]. Other impulse noise mitigation algorithms include the time/frequency domain reduction and estimation schemes in [41], [42] and [43], the iterative impulse noise suppression strategy in [44], [45] and [46], the null-subcarriers based impulse noise position detection technique in [47], and the sparse signal reconstruction algorithm based impulse noise estimation and cancellation scheme in [48].

It is worth pointing out that when the impulse noise in the wireless channel is represented by the Middleton Class A or the Bernoulli-Gauss model, the OFDM impulse noise cancellation algorithms mentioned above are effective solutions for long packet transmission with long preambles. In the case of the WirelessHP system considered in this research, the impulse noise is typically non-Gaussian, and the data OFDM frame is designed for short-packet transmission with only one OFDM symbol as the preamble. It would be long-term research to develop an effective impulse noise cancellation algorithm for complicated industrial wireless channels through hardware experiments. In this paper, we focus on mitigating the deleterious effect of impulse noise through interleavers, while the impulse noise cancellation algorithms are not employed.

C. WirelessHP and its developments

In the existing industrial wireless communication standards, WirelessHART and WIA-PA are the modified versions of the IEEE 802.15.4 standard, while WIA-FA originated from the IEEE 802.11g/n standard [7]. Although these standards facilitate easier deployment and faster popularization, they are not suitable for the low latency requirement in PSA and PEC for critical applications. The primary reason is that the physical layers of the IEEE 802.15.4 and IEEE 802.11g/n are designed with long preambles for long packet transmission, so neither of these technologies is optimal for achieving ultra-low latency short-packet transmission.

A new paradigm, WirelessHP, is proposed to alleviate the efficiency problems with short-packet transceiving by adopting innovative solutions to its physical layer [8]. Firstly, to enable fast packet detection, synchronization and channel estimation, one OFDM symbol is used as a preamble. With static positions of transmitter and receiver nodes and short communication distance, such a short preamble suffices. It is also assumed that fixed Time Division Multiple Access (TDMA) is used with the predefined cyclic transmission, so controllers and sensor/actuator nodes know at which time slot a data OFDM frame is to be transmitted or received. Secondly, packet length is minimized. As network topology (star) and locations of the central controller, sensors and actuators are static, most network parameters, such as the number of nodes and long addresses, need not be transmitted in each packet. Other parameters for the physical layer settings, like the channel coding schemes, code rate and packet length, are set in the network initialization stage and can also be omitted from the packet overhead, thus further minimizing the packet length.

Figure 1 illustrates the WirelessHP data OFDM frame structure in time and frequency domains. For a coded packet length of some $10^{2}$ bits, one data OFDM frame is composed of one OFDM preamble and a number of data OFDM symbols. By comprehensive parameters optimization to meet the extremely low latency requirement [8], a 5 MHz frequency band is evenly divided into 32 subcarriers, among which 4, 1, and...
6 subcarriers are devoted to pilot, nulled direct current and guard subcarriers, while the remaining 21 subcarriers are used for data transmission. The number of data OFDM symbols is determined by four factors: the message packet length, the modulation order, the code rates, and the number of data subcarriers. Figure 2 explains the block diagrams of the WirelessHP transmitter and receiver. On the transmitter side, the message packet is first processed by the scrambler. Then the coded packet is evenly divided into \( N_{\text{data}}^{\text{sym}} \) parts (seen Eq. (7)), and bits in each part are assigned to the data subcarriers for modulation. By using Fast Fourier Transform (FFT), the pilot, nulled direct current, guard and data subcarriers are combined to form data OFDM symbols. Subsequently, the preamble and data OFDM symbols are assembled to create one data OFDM frame. In the transmission module, the OFDM data frame is modulated to a central frequency for transmission. On the receiver side, the preamble OFDM symbol in the received frame is extracted for synchronization, frequency offset and channel estimation, which are then used to demodulate the data OFDM symbols. In the data OFDM symbols, the pilot subcarriers are extracted to correct the phase error for more accurate data subcarriers demodulation. After being processed by the channel decoder and descrambler, the received packet is used for data refresh.

Based on the practical experiments, [8] demonstrated the effectiveness of the WirelessHP physical layer protocols. Furthermore, it shows that the transmission duration of a 100 bits message packet can be shortened to 1.6 µs if a 160 MHz bandwidth is used. [49] proposed a fast packet detection algorithm with a single OFDM symbol as the preamble. By adopting the differential detection and prediction mechanisms, a packet detection error rate in the order of \( 10^{-6} \) is verified. Channel coding is proven to be an effective way to improve PER when incorporated into the WirelessHP physical layer, with only a slight increase in transmission latency [50]. [14] investigated the influence of modulation order and transmission efficiency on coded short-packet transmission. This work was the first to report that \( 10^{-7} \) PER is achievable in real factory environments.

D. Interleaved coded transmission

The full potential of interleavers to improve transmission reliability was realized with the invention of turbo codes in [51]. To improve the PER performance in a fading channel, [52] presents a novel mechanism by interleaving the coded bits before being modulated for wireless transmission. Based on the analysis in [53], channel coding can improve PER performance if the channel interleaver is long enough to take advantage of the diversity effect. On the other hand, for applications that require a high degree of delay sensitivity, such as industrial wireless control with short control packets, the entire transmitted packet may encounter the same interference if the transmission duration is shorter than the interfering duration [54]. The resulting block fading effect thus cannot provide sufficient diversity.

Shannon limit approaching coding schemes, such as the turbo and Low Density Parity Check (LDPC) code families, have been incorporated with interleavers to improve error correction capability [55], [56], as this traditional and straightforward technique is an effective solution for long packets. However, on the condition of short-packet transmission, these codes are not superior to traditional convolutional/block codes [57]. Considering the high error floor and high latency introduced by iterative decoding of turbo and LDPC codes for short-packet transmission, turbo and LDPC codes are less preferred for industrial wireless control purposes. Traditional coding schemes, such as Convolutional Codes (CC) and RS codes, are usually adopted for industrial scenarios where both latency and reliability are essential [22], [54]. Most works concern theoretical analyses using idealized channel models [55], [56]. Unfortunately, these assumptions cannot reflect the fundamental characteristics of industrial environments. The interleaved coded transmission tests in [22] were performed in a factory environment. However, the physical layer structures of the employed wireless communication standards (IEEE 802.15.4 and IEEE 802.11) are quite different from the WirelessHP system considered in this work.

III. INTERLEAVERS FOR THE WIRELESSHP PHYSICAL LAYER

As reviewed in Section II-B and C, in OFDM, the data bits are mapped on a number of subcarriers, and then these bits are transmitted in parallel using FFT. With the longer OFDM symbol duration, the impulse noise spectrum is spread over all subcarriers. Thus OFDM is robust to the impulse noise with low energy. As the impulse noise energy is spread in the
range of one OFDM symbol, the superiority may lose in the case of high-energy impulse noise. A possible solution is to incorporate interleaver into the WirelessHP physical layer. By incorporating an interleaver on the transmitter side, bits in the coded short-packet can be relocated within the data frame of an OFDM system. By viewing from the time domain on the receiver side, the high-power impulse noise impaired samples in one OFDM symbol are spread in more OFDM symbols after deinterleaving. In this paper, we explore the feasibility of applying bit interleaving in the WirelessHP physical layer with the following unique characteristics.

- Only one OFDM symbol is employed in the WirelessHP physical layer as the preamble, then fast synchronization and channel estimation algorithms are employed for packet detection and OFDM demodulation. While these techniques can significantly reduce transmission latency, the effect on demodulation and decoding performance should be considered, because multi-path fading and interference from other wireless devices working in the same band are important factors which may impair synchronization and channel estimation.

- Industrial control applications require $10^{-6}$ to $10^{-9}$ level of PER to guarantee stable operation [58]. With a lower code rate, [14] has shown that $10^{-7}$ PER is achievable and also found that high energy impulse will cause severe PER degradation. As OFDM can withstand the weak energy impulse with low frequency, the PER performance deteriorates rapidly when the impulse energy or frequency increases. Although high energy or high frequency impulse noise may represent the worst cases in industrial scenarios, and the probability is low, the PER degradation should be seriously addressed if ultra-high reliability is definitely required.

- In industrial applications targeted by WirelessHP, impulse interference represents the main type of interference leading to burst errors in the received packet. Especially, the impulse duration is much shorter than that of the data OFDM symbol. To achieve ultra-high reliability while keeping the latency overhead at an acceptable level for 100 bits short-packet transmission, redistributing the position of the corrupted bits within the packet is a preferred option. This has not yet been addressed for WirelessHP and related literature.

To investigate the effectiveness of interleavers in the WirelessHP physical layer, four kinds of interleaver are evaluated. Note that $L$, $L_2$ and $N_{data}^{sym}$ are explained in Section IV-A.

1) Packet block interleaver - By assuming $M$ and $N$ as the number of rows and columns respectively, a packet block interleaver can be modeled by a $M \times N$ matrix. First, all $L_2$ bits in a coded packet are written into the $M \times N$ matrix row by row. Then, the interleaved packet is output by reading out bits from the matrix column by column. It is worth pointing out that the bits can be written into and read out in different manners [59]. In our experiments, bits in the coded packet are written into each row of the matrix from the left side to the right side. Then start from the right column, the interleaved bits are read out from top to bottom, as illustrated in Figure 3 with an example of $L_2 = 8$ bits. $M$ and $N$ are the matrix parameters calculated by Eq. (1) and (2), respectively. The value of $L_3$, i.e. the number of zero bits padded to fit the interleaver length, is given by Eq. (3).

\[ M = \left\lceil \sqrt{L_2} \right\rceil + 1 \]  
\[ N = \begin{cases} M - 1, & \text{if } M (M - 1) \geq L_2 \\ M, & \text{if } M (M - 1) < L_2 \end{cases} \]  
\[ L_3 = M \times N - L_2 \]  

2) Symbol block interleaver – For a packet block interleaver, bits are redistributed in the range of a whole data OFDM frame. However, for a symbol block interleaver, the padded bits and coded bits are partitioned into $N_{data}^{sym}$ parts. Each part corresponds to one OFDM symbol, and interleaving is performed within each part. Since each part can be interleaved/deinterleaved in parallel, processing latency can be significantly reduced compared to packet block interleaving. In this research, Binary Phase Shift Keying (BPSK) is employed for modulation, and each OFDM symbol includes 21 data subcarriers. Therefore, each part contains 21 bits. Similar to the way shown in Figure 3, the 21 bits are interleaved by using a $3 \times 7$ matrix.

3) 3GPP interleaver - As a quadratic polynomial permutation interleaver designed for the Long Term Evolution Advanced (LTE-Advanced) turbo codes in [60], the 3GPP interleaver reduces the correlation between adjacent bits with low hardware overhead. Assuming $Y = Y_0, Y_1, \cdots, Y_i, \cdots, Y_{K-1}$ as a coded packet, $Y' = Y_0, Y'_1, \cdots, Y'_i, \cdots, Y'_{K-1}$ as the interleaved packet, where $K$ is the packet length. The interleaved bit $Y'_i$ is corresponding to the bit $Y_{\pi(i)}$ in the coded packet $Y$, and $\pi(i)$ is computed by Eq. (4).

\[ \pi(i) = (f_1 \cdot i + f_2 \cdot i^2) \mod K \]  
where $f_1$ and $f_2$ are the interleaving coefficients for a packet length $K$ that predefined by the LTE-Advanced standard [61]. For example if $K = 120$, $f_1$ is 103 and $f_2$ is 90. To fit the coded packet length $L_2$, $K$ is chosen as follows: i) $K$ is greater or equals to $L_2$. ii) The number of padded zeros bits $L_3 = K - L_2$ should be as small as possible.
**IV. EXPERIMENTAL SETUP**

A. Hardware deployment of the experiment

According to Figure 5 (a), an interleaving module is placed between the channel encoder and the OFDM modulation modules, enabling the coded bits to be interleaved for wireless transmission. Figure 5 (b) illustrates the receiver diagram. The deinterleaving module is involved within a single OFDM symbol (for the symbol block interleaver) or within multiple OFDM symbols (for the other three interleavers) to disperse bit error bursts caused by time-domain impulse interference and/or frequency-domain narrowband interference. This should increase the possibility of recovering those erroneous bits by the error correction algorithm. Hardware deployment of the experiment is also presented in Figure 5. Two Ettus USRPs X310 are deployed with a Line-of-Sight (LOS) distance of 10 meters. Both USRPs function as the transmitter and receiver, and both are connected to a PC with a Gigabit Ethernet cable to form the USRP-PC hardware testing platform. The practical scenario is illustrated in Figure 6: The experiments were conducted in an operating automated tea production workshop with a space of 42.1, 9.6 and 3.75 meters for length, width and height, respectively. Both USRP systems are perched on trolleys, and are configured to set up a LOS testing scenario. Antennas used are W1910 penta band stubby models for an 866.5 MHz central frequency and a bandwidth of 5 MHz. Considering a typical industrial environment is shared by many wireless devices, the transmission power of each device is limited to avoid mutual interference. In this research, the effective transmission power is approximately 18 dBm, since the transmission power for USRP X310 is 17 dBm when the transmission gain is set to 15 [63], and the peak antenna gain is 1 dB at the frequency of 866.5 MHz.

\[ L_2 + L_3 = 156, \text{ the number of data OFDM symbols is } N_{data} = 8 \text{ based on Eq. (7). Consequently, } L_4 = 12 \text{ zero bits are padded to the interleaved 156-bit packet for OFDM modulation by Eq. (8).} \]
As reviewed in Section II-C, WirelessHP mainly concentrates on improving the short-packet transmission efficiency. On the physical layer, the numbers of the guard, pilot and data subcarriers have been optimized, while the subcarrier modulation order parameter is optional [8]. In a noisy factory environment, [14] presented a comprehensive investigation of the PER performance for different modulation orders. With the same data OFDM frame duration, distance and transmission power, BPSK is superior to Quadrature Phase Shift Keying (QPSK) and 8 Phase Shift Keying (8PSK) in terms of PER. Although high order modulation can avail the advantage of interleaving burst error bits for long packet transmission, it may not be suitable for industrial wireless control applications, where the message packet is short and the transmission power should be limited to an acceptable level. Therefore, BPSK is used in this research. As shown in Figure 5 (a), the 100 bits message packet is processed as follows before arriving at the OFDM modulation module:

1) On the transmitter USRP-PC side, $L_1$ zero bits are padded to the $L$ data bits to adjust the packet length for encoding, where $L_1$ and the coded packet length $L_2$ is computed by Eq. (5) and (6), respectively. Note that the code rate $R$ is an irreducible fraction, and $R_o$ is the numerator of $R$.

$$L_1 = \left\lfloor \frac{L}{R_o} \right\rfloor \times R_o - L$$

(5)

$$L_2 = \frac{L + L_1}{R}$$

(6)

2) Each coded packet is padded with $L_3$ zero bits, if necessary, to fit for the interleaver length. Given that BPSK is used for the subcarriers modulation and each data OFDM symbol has 21 subcarriers for data transmission, the number of data OFDM symbols $N_{data}^{sym}$ can be computed by Eq. (7). Since $N_{data}^{sym}$ is an integer, $L_4$ zero bits should be padded to the interleaved packet for OFDM modulation, which is given by Eq. (8).

$$N_{data}^{sym} = \left\lfloor \frac{L_2 + L_3}{21} \right\rfloor$$

(7)

$$L_4 = N_{data}^{sym} \times 21 - (L_2 + L_3)$$

(8)

As shown in Figure 5 (b), a reverse procedure is performed on the receiver USRP-PC side. After OFDM demodulation, deinterleaving and decoding, the corresponding zero bits are removed for further processing. For the purpose of real-time industrial wireless control, the correctness of a decoded packet should be seriously checked. Because of the high packet refresh rate in critical applications, a corrupted packet may lose its significance even after being retransmitted, since it arrives too late to reflect the latest status of the perceived parameter. When it comes to the specific industrial wireless control applications, the reliability is usually assessed by PER, while bit error rate and symbol error rate are of less significance. Consequently, PER is used in this research for analysis.

### B. Generation of impulse interference waveforms

In the IEEE 1613 standard [11], a series of clauses address the impulse interference testing for communications devices, such as Ethernet hubs, switches and routers installed in power transmission and distribution facilities. These include the SWC test parameters of impulse waveforms, the testing chamber and the environment setup. In specified scenarios, the tested devices are exposed to impulse voltage shocks in the order of thousands of volts. According to observed and measured data in actual substation installations, the impulse waveforms are modelled by parameters in Table I.

Switching power supply systems are another vital source of impulse interference. Featured with small size, low cost, and high conversion efficiency, the switching techniques are widely used in converters for industrial applications [64]. To increase power density and efficiency, the switching frequency should be increased. Limited by the rising switching loss at the higher switching frequency, common Si-Insulated Gate Bipolar Transistor (IGBT) high power inverters are operated at under 20 kHz frequency [65], while state-of-the-art Si power Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) converters operate at less than 200 kHz in low power applications [66]. With recent progress in the semiconductor material and manufacturing technologies, the higher breakdown voltage and lower on-resistance advantages are exploited to develop high-switching frequency power components. In [67], the gallium nitride (GaN) switches are employed to realize a 65 W flyback converter working at 340 kHz with a peak efficiency of about 90%. An improved prototype, i.e. the quasi-resonant converter, is proposed in [68] with 12V/3A output and switching frequency of 1 MHz. By using silicon carbide (SiC) MOSFET as the core switching component, [65] has built a 20 KW grid inverter working at 300 kHz, and Se-Hong Park et al. went further by increasing the switching frequency to 4 MHz for a 10 KW inverter [69]. When the wireless communication system gets power from the same source as the electrical equipment, the high frequency switching power introduced...
TABLE I
IMPULSE INTERFERENCE WAVEFORM PARAMETERS OF IEEE 1613 STANDARD SWC TESTS

| Waveform polarity | Magnitude | Impulse duration | Frequency | Testing duration |
|-------------------|-----------|------------------|-----------|-----------------|
| Positive & Negative | 4 Kilovolts | Tolerance ±10% 50 ns | 2.5 kHz | ≥ 1 minute |
|                   | Tolerance ±10% 50% value |                  |         |                 |

Impulse interference can break into the baseband through the ground wire, and the power supply system originated impulse interference may interfere with the transmitted data frame waveforms [70], [71].

Moreover, suppose an independent power supply is used for a wireless communication system. In that case, non-linear effects may cause the surge and switching pulses to generate impulse interference in the radio frequency bands where the wireless communication system operates. Therefore, investigating the impact of high-frequency switching power supply systems on WirelessHP is an important topic in industrial applications. The 2.5 kHz frequency value in Table I was specified by IEEE 1613 standard in 2013 and does not reflect the increased switching frequency in today’s converters. Hence this paper considers impulse interference frequency up to 700 kHz.

The impulse interference is modelled by referring to the relevant clauses in the IEEE 1613 standard. For impulse interference with frequency ranges from 50 to 700 kHz, the impulse is rectangular and bipolar, while the duration is chosen as 100 ns, since this assumption is considered typical in a factory environment [11], [12]. Regarding the impulse power, \( \Gamma \) is defined as the ratio of the impulse peak power \( P_{ip} \) to the average power of the WirelessHP data OFDM frame \( P_{tp} \), and is calculated by Eq. (9) as below.

\[
\Gamma = 10 \cdot \log_{10} \frac{P_{ip}}{P_{tp}} \quad \text{(dB)} \tag{9}
\]

In the impulse interference resisting capability testing, the transmitting USRP X310 has the same setup as described in Section IV-A. A Matlab program was designed to generate impulse interference waveforms by a USRP N210, which then modulates these waveforms to the central radio frequency of 866.5 MHz. This impulse interference signal is added to the transmitter antenna via a three-way connector, as shown in Figure 7. By adjusting the transmitting gain of the USRP N210, the value of \( \Gamma \) is set for four levels for practical experiments. Examples of the generated impulse interference waveform, the transmitted packet waveform, and their combined waveform are shown in Figure 8. It is worth pointing out that, based on the USRP parameters setup, the duration of each OFDM symbol is 6.8 \( \mu \text{s} \). The data OFDM frame in Figure 8 (b) has 11 symbols with a whole duration of 74.8 \( \mu \text{s} \).

![Fig. 7. Connection of impulse interference generator USRP N210 to transmitter USRP X310.](image)

![Fig. 8. Examples of waveforms.](image)

V. EVALUATION OF INTERLEAVERS IN WIRELESSHP PHYSICAL LAYER FOR SHORT-PACKET TRANSMISSION

Four types of interleaver are implemented on the USRP-PC platform. CC, RS and RS+CC concatenated codes are applied...
to generate bit interleaved packets for OFDM transmission. In the receiver Matlab program, the decoding algorithm for CC and RS codes is the hard decision Viterbi and Berlekamp-Massey algorithm, respectively. A set of experiments, lasting over seven months, were conducted in real factory environments. This section first analyzes the effect of interleavers on PER performance for coded packets. Then the resilience of interleavers with these codes is investigated. Note that in practice, PER depends on the actual factory environments where the wireless communication system is deployed. In this research, we show how PER is affected by different interleavers and codes, for given impulse interference frequency and power.

Figure 9 indicates the PER performance improvements by applying four types of interleavers in the testing scenario shown in Figure 6. As presented in these figures, in most cases lower PERs are achieved by using these interleavers. Compared with cases when packet block interleaver, symbol block interleaver and no interleaver are applied, PER performance of the 3GPP and S-random interleavers is much better. This may be because the 3GPP and S-random interleavers disperse adjacent bits to a wider distance. For example, when the S-random interleaver is employed, the positions of neighbor bits are moved to a minimal distance of 5 bits. Thus interleaving is an effective solution to improve the reliability for short-packet transmission in factory environments.

Among the four interleavers, the symbol block interleaver achieves the slightest PER performance improvement. This can be explained by the fact that the symbol block interleaver moves bit position only within a 21-bit OFDM symbol, while in the other interleavers, bits are interleaved within the whole data OFDM frame. However, the PER with symbol block interleaver is still lower than that without any interleavers in most cases. According to [22], the PER performance may be degraded by using interleaver in the Additive White Gaussian Noise (AWGN) channel, so our results may indicate that the channel in the testing environments has narrowband interference. Furthermore, considering that the packet block interleaver, 3GPP interleaver and S-random interleaver achieve better PER improvement than the symbol block interleaver, it indicates that impulse interference crossing multiple OFDM symbols causes burst errors in the received packet. Hence, interleaving performed in the time domain helps to resist impulse interference.

B. Extreme PER performance testing against high frequency impulse interference

The experimental results of Figure 9 do not give a systematic analysis of the effect of interleavers on PER performance. Hence in this section, the performance of the interleavers against impulse interference is investigated using impulse interference generated by a USRP N210. To explore the extreme performance, the interference power ratio $\Gamma$ is selected as 0, 9.54, 17.5 and 20 dB, as these values cover a range where the PER changes from slightly degraded to complete failure. CC(1/2) and RS(31, 21)+CC(1/2) concatenated codes are selected for this investigation, since they outperform the other codes in the high reliability region. For CC(1/2) coded transmission, the results are presented in Figure 10. Power ratio $\Gamma$ and impulse frequency are the key factors that affect PER performance. The power of the impulse interference depends on the emission power of the interference and the propagation mechanism (in particular the distance) from the interference source to the wireless receiver antenna. It should be noted that...
be pointed out that higher impulse frequency increases the number of impulses per data OFDM frame, which means higher interference energy (at given interference peak power) affecting the transmitted packets. As seen in Figure 10 (a), (b) and (c), when the impulse frequency is 50 kHz, the results show that using interleaver can improve the PER performance, and the PERs are only slightly degraded by the power ratio \( \Gamma \). This phenomenon means when only a small number of impulse waveforms are included in a data OFDM frame, the interleaved coded strategy still can correct the corrupted bits on the condition of lower/moderated impulse interference power. Moreover, when the PERs of Figure 10 (a), (b) and (c) at 50 kHz are compared with that of Figure 9 (a) at the code rate of 1/2, we find the PER values are very similar for the tested interleavers and no interleaver case. As the impulse frequency increases, the testing results show that using interleaver is not preferred to improve the reliability. The reason can be explained as follows: due to the excessive number of impulses in a short-packet, the impulse interference power and duration are higher. Consequently, the deinterleaving process cannot disperse all burst bits and may likely generate new burst errors in a short range. In Figure 10 (d) where \( \Gamma \) is increased to 20 dB, the PERs are drastically descended to the range of \( 1.3 \times 10^{-2} \sim 1 \). This phenomenon reflects the fact that the WirelessHP transmitting/receiving mechanism, to a certain degree, can endure the shock of impulse interference, but will collapse when the impulse interference power reaches a strong level (\( \Gamma = 20 \) dB in this research).

In the tests with RS(31, 21)+CC(1/2) coded packet, \( \Gamma = 0 \) dB was not considered in Figure 11 (a), since in this case PER is very low, in the order of \( 10^{-7} \). Instead, \( \Gamma = 6.02 \) dB is used in Figure 11 (a), while in Figure 11 (b), (c) and (d), \( \Gamma \) with the same values are selected as in Figure 10 (b), (c) and (d). Comparing PER in Figure 10 and 11 the following is concluded: i) At a low power ratio \( \Gamma \) (< 6.02 dB), the RS(31, 21)+CC(1/2) concatenated code is superior to CC(1/2). This is also consistent with the results shown in Figure 9 (a) and (c). ii) As the value of \( \Gamma \) increases (6.02 \sim 20 \) dB), the RS(31, 21)+CC(1/2) concatenated code loses its superiority over the CC(1/2). Since RS(31, 21)+CC(1/2) is a concatenated coding scheme with a lower code rate, the coded packet is longer. Hence there may be more bits are corrupted by the impulse noise when the packet is transmitted through the bursty wireless channel.

The above analysis implies the correlation between the PER performance and the number of impulses in each data OFDM frame. Taking the S-random interleaver as an example, the comparison of PER versus the number of impulses in one frame is presented in Figure 12. For the CC(1/2) with 74.8 \( \mu s \) and the RS(31, 21)+CC(1/2) with 108.8 \( \mu s \) data OFDM frame
duration, respectively. As can be expected, the PER drops with the increase of impulse number. The higher the impulse noise energy, the faster degradation of the reliability. As the interleaved coded transmission scheme can tolerate weak impulse noise interference, this advantage no longer exists as the impulse noise energy increases, especially for the lower code rated RS\( (31, 21) + \text{CC}(1/2) \). The rationale behind this phenomenon is that RS\( (31, 21) + \text{CC}(1/2) \) is a concatenated code. For a 100-bit packet, the packet length is 155 bits after RS\( (31, 21) \) encoding. Consequently, the overall packet length is 310 bits after the CC\( (1/2) \) encoding, versus the 200 bits length when only CC\( (1/2) \) is employed. From the statistical point of view, we assume the same bit error rate for CC\( (1/2) \) coded packet. The 155-bit RS codewords include more error bits than the 100-bit packet after Viterbi decoding. PER of the 155-bit RS codewords is higher than the 100-bit message packet. So, improved PER can be achieved after the RS decoding for weak impulse noise. However, in case of strong impulse noise interference, the RS decoder cannot correct the error bits, and thus worse PER is expected.

Based on the above experimental results, the PER curves degraded gradually when \( \Gamma \leq 17.5 \) dB, which shows the impulse noise power is in the linear input range of the receiver USRP radio frequency (RF) front-end. As \( \Gamma \) is increased to 20 dB, the impulse noise peak power is 100 times the data OFDM frame transmission power. The PER almost reaches 1 as the impulse frequency increases. Consequently, we suppose this level of impulse noise power represents the most severe case that the USRP-PC hardware platform can withstand. In real industrial environments, there may exist more powerful impulse interference, for example, 25 dB malicious jamming attack, that can saturate the receiver USRP RF front-end. Restricted by the nonlinear effects, samples of the impulse noise in the receiver USRP are similar to the case of 20 dB impulse noise. The WirelessHP system only has one OFDM symbol as the preamble and is less robust to the high-energy impulse surge. Functionalities, such as synchronization, channel estimation, frequency offset and phase correction, will completely collapse to invalid operation, resulting in sudden degradation of the PER performance.

C. Discussion of interleavers in short-packet transmission

To summarize, when interleaver is employed for short-packet transmission, impulse interference energy, interleaver structure and coding scheme are the three mutually dependent factors that determine PER performance:

- The impulse interference energy and frequency are the crucial factors affecting the reliability. On conditions of strong impulse interference and high switching frequency, the improvements of PER performance are small, or degraded when compared with the no interleaver case. Consequently, interleavers are completely unnecessary in extreme scenarios. However, there is still room to use interleavers if the impulse energy and frequency are within a certain range. Good interleavers, such as the 3GPP and S-random interleavers, can achieve better PER performance by relocating neighbor bits to a longer minimal distance. For coded short-packet transmission, interleavers with longer minimal distance are more suitable for impulse noise deteriorated wireless channels.

- Interleaver performance tends to depend on the coding schemes. For codes with moderate error correction capability, i.e. the RS\( (31, k) \) and RS\( (31, k) + \text{CC}(5/6) \) codes in Figure 9, the interleavers are more significant in affecting the PER performance, as compared to the more powerful CC\( (1/2) \) and RS\( (31, k) + \text{CC}(1/2) \) concatenated codes. A similar phenomenon can also be found in Figure 10 and 11 where CC\( (1/2) \) and RS\( (31, 21) + \text{CC}(1/2) \) concatenated codes are compared, especially in cases of low power ratio \( \Gamma \) and high impulse frequency region. As an observed phenomenon, this correlation should be further investigated.

Based on these analyses, impulse interference energy and frequency are the main parameters determining the usefulness
of interleavers in coded short-packet transmission. Different interleavers deliver different PER performance improvements for different codes. The selection of interleavers also depends on the expected characteristics of interference. In practice, it is of most importance to select a method which is most robust to the widest range of impulse and other interference characteristics.

VI. CONCLUSIONS

For the WirelessHP system featured with one OFDM symbol as the preamble and 100-bit level short-packet for transmission, this paper investigates the feasibility of applying bit interleaving to its physical layer in a factory environment. Based on the constructed USRP-PC hardware platform for the WirelessHP system, we show that bit interleaving in coded short-packet can improve the reliability. Given the same coding scheme, the interleaver structure is essential for improving PER performance. By generating impulse interference with different power levels, we have tested the resilience of interleavers in practical scenarios. We show that the PER improvement depends more on the energy and frequency of impulse interference, while the influence of the interleaver structure is less significant. Due to the fact that PER improvement is affected by a series of interdependent factors, a thorough investigation is required to find effective solutions, including the OFDM impulse noise cancellation and smart decoding algorithms, to detect and mitigate the reverse effect of impulse noise for ultra-high reliability industrial wireless control applications.

ACKNOWLEDGMENTS

The authors would like to thank the Editors and the anonymous Reviewers for their valuable comments to improve the presentation of this paper.

REFERENCES

[1] Z. Pang, M. Luvisotto, and D. Dzung, “Wireless high-performance communications: The challenges and opportunities of a new target,” IEEE Ind. Electron. Mag., vol. 11, no. 3, pp. 20–25, Sep. 2017.
[2] HART Field Communication Protocol Specification, Revision 7.0, HART Communication Foundation Std., 2007. [Online]. Available: http://www.hartcomm.org/
[3] IEC PAS 62948: Industrial networks - Wireless communication network and communication profiles - WIA-PA, International Electrotechnical Commission (IEC) Std., 2015.
[4] IEC PAS 62948: Industrial networks - Wireless communication network and communication profiles - WIA-PA, International Electrotechnical Commission (IEC) Std., 2015.
[5] S. Feliciano, H. Sarmento, and J. de Oliveira, “Field area network in a MV/LV substation: A technical and economical analysis,” in Proc. IEEE Int. Conf. Intell. Energy Power Syst. (IEPS), Jun. 2014, pp. 192–197.
[6] D. Cottet, W. Merwe, F. Agostini, G. Riedel, and D. Dzung, “Integration technologies for a fully modular and hotswappable MV multi-level concept converter,” in Proc. PCIM Eur. Conf. Proc. (PCIM), May 2015, pp. 1–8.
[7] M. Luvisotto, Z. Pang, and D. Dzung, “Ultra high performance wireless control for critical applications: Challenges and directions,” IEEE Trans. Ind. Inf., vol. 13, no. 3, pp. 1448–1459, Jun. 2017.
[8] M. Luvisotto, Z. Pang, D. Dzung, M. Zhan, and X. Jiang, “Physical layer design of high performance wireless transmission for critical control applications,” IEEE Trans. Ind. Inf., vol. 13, no. 6, pp. 2644–2654, May 2017.
[9] R. Zurawski, G. Scheible, D. Dzung, J. Endresen, and J. Frey, Networked Embedded Systems, CRC Press, 2009.
[10] A. Apostolov, M. Dood, and J. Tengdin, “Developing IEEE 1613 standards for communications network in substations,” IEEE Power Energy Mag., vol. 2, no. 1, pp. 73–75, Feb. 2004.
[11] IEE Standard Environmental and Testing Requirements for Communication Networks Devices Installed in Transmission and Distribution Facilities, IEE 1613 Std., 2013.
[12] J. T. Tengdin, K. Fodero, and R. Schwartz, “Ensuring error-free performance of communications equipment,” SEL Journal of Reliable Power, vol. 3, no. 2, pp. 4–11, Aug. 2012.
[13] M. Luvisotto, Z. Pang, and D. Dzung, “High-performance wireless networks for industrial control applications: New targets and feasibility,” P IEEE, vol. 107, no. 6, pp. 1074–1093, Jun. 2019.
[14] M. Zhan, Z. Pang, D. Dzung, M. Luvisotto, K. Yu, and M. Xiao, “A new wireless high-performance control: 10−9 packet error rate in real factory environments,” IEEE Trans. Ind. Inf., vol. 16, no. 8, pp. 5554–5564, Aug. 2020.
[15] V. Sethuraman and B. Hajek, “Comments on “bit-interleaved coded modulation”,” IEEE Trans. Inf. Theory, vol. 52, no. 4, pp. 1795–1797, Apr. 2006.
[16] A. Martinez, A. Martinez, and G. Caire, Bit-Interleaved Coded Modulation. Now Foods, 2008.
[17] A. Martinez, A. G. i Fabregas, G. Caire, and F. M. J. Willems, “Bit-interleaved coded modulation in the wideband regime,” IEEE Trans. Inf. Theory, vol. 54, no. 12, pp. 5447–5455, Dec. 2008.
[18] Z. Hong and B. L. Hughes, “Bit-interleaved space-time coded modulation with iterative decoding,” IEEE Trans. Wireless Commun., vol. 3, no. 6, pp. 1912–1917, Nov. 2004.
[19] C. Choi and G. Im, “Bit-interleaved coded multilevel modulation for single-carrier frequency-division multiplexing communication,” IEEE Commun. Lett., vol. 14, no. 3, pp. 193–195, Mar. 2010.
[20] A. A. Abotabl and A. Nosratinia, “Broadcast coded modulation: Multi- level and bit-interleaved construction,” IEEE Trans. Commun., vol. 65, no. 3, pp. 969–980, Mar. 2017.
[21] Y. Jin, X. Xia, Y. Chen, and R. Li, “Full-duplex delay diversity relay transmission using bit-interleaved coded OFDM,” IEEE Trans. Commun., vol. 65, no. 8, pp. 3250–3258, Aug. 2017.
[22] B. Filip, M. Gidlund, and T. Zhang, “Channel coding and interleaving in industrial WSN: Abiding to timing constraints and bit error nature,” in Proc. IEEE Trans. Instrum. Meas. (M&N), Oct. 2013, pp. 46–51.
[23] M. Zhan, Z. Pang, K. Yu, and D. Dzung, “Interleaver in coded short packet transmission: A preliminary result,” in Proc. IEEE Int. Workshop Factory Commun. Syst. (WFCS), July 2021, pp. 111–114.
[24] D. Middleton, An introduction to statistical communication theory. McGraw-Hill New York, 1960.
[25] D. Middleton, “Statistical-physical models of electromagnetic interference,” IEEE Trans. Electromagn. Compat., vol. 19, no. 3, pp. 106–127, Aug. 1977.
[26] M. Ghosh, “Analysis of the effect of impulse noise on multicarrier and single-carrier QAM systems,” IEEE Trans. Commun., vol. 44, no. 2, pp. 145–147, Feb. 1996.
[27] I. Mann, S. McLaughlin, W. Henkel, R. Kirkby, and T. Kessler, “Impulse generation with appropriate amplitude, length, inter-arrival, and spectral characteristics,” IEEE J. Sel. Areas Commun., vol. 20, no. 5, pp. 901–912, Jun. 2002.
[28] S. Galli, A. Scaglione, and Z. Wang, “For the grid and through the grid: The role of power line communications in the smart grid,” P IEEE, vol. 99, no. 6, pp. 998–1027, Jun. 2011.
[29] D. Tseng and T. Chang, “Robust decoding for OFDM systems in memory impulse channels,” in Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm), Nov. 2015, pp. 677–682.
[30] M. Sliškovici, “Signal processing algorithm for OFDM channel with impulse noise,” in Proc. IEEE Int. Conf. Electron., Circuits Syst., Proc. (ICECS), Dec. 2000, pp. 222–225.
[31] M. Zimmermann and K. Dostert, “Analysis and modeling of impulse noise in broad-band power-line communications,” IEEE Trans. Electromagn. Compat., vol. 44, no. 1, pp. 249–258, Feb. 2002.
[32] G. Ren, S. Qiao, H. Zhao, C. Li, and Y. Hei, “Mitigation of periodic impulse noise in OFDM-based power-line communications,” IEEE Trans. Power Deliv., vol. 28, no. 2, pp. 825–834, Apr. 2013.
[33] IEC 61748-3: Industrial communication networks - Profiles - Part 3: Functional safety fieldbuses - General rules and profile definitions, International Electrotechnical Commission (IEC) Std., 2017.
[34] S. V. Zhidkov, “Impulsive noise suppression in OFDM-based communication systems,” IEEE Trans. Consum. Electron., vol. 49, no. 4, pp. 944–948, Nov. 2003.
35] J. Lechleider, “An adaptive impulse noise canceller for digital subscriber lines,” in Proc. GLOBECOM IEEE Global Telecommun. Conf. (GLOBECOM), Dec. 1992, pp. 36–39.

36] G. V. Meerbergen, M. Moonen, and H. D. Man, “Combining Reed-Solomon codes and OFDM for impulse noise mitigation: RS-OFDM,” in Proc. IEEE Int. Conf. Acoust. Speech Signal Process Proc. (ICASSP), May 2006, pp. IV–IV.

37] J. Rinne, J. Henriksso, and A. Hazmi, “Impulse noise canceller for OFDM system utilizing pilots,” in Proc. 7th Int. OFDM-Workshop, Sep. 2002, pp. 183–187.

38] J. Rinne, A. Hazmi, and M. Renfors, “Impulse burst position detection and channel estimation schemes for OFDM systems,” IEEE Trans. Consum. Electron., vol. 49, no. 3, pp. 539–545, Aug. 2003.

39] S. V. Zhidkov, “Analysis and comparison of several simple impulsive noise mitigation schemes for OFDM receivers,” IEEE Trans. Commun., vol. 56, no. 1, pp. 5–9, Jan. 2008.

40] S. V. Zhidkov, “On the analysis of OFDM receiver with blanking nonlinearity in impulsive noise channels,” in Proc. Int. Symp. Infor. Sign. Process. Commun. Syst. (ISPACS), Nov. 2004, pp. 492–496.

41] J. Armstrong and H. A. Suraweera, “Impulse noise mitigation for OFDM using decision directed noise estimation,” in Proc. Eighth IEEE Int. Symp. Spread Spectrum Tech. Appl. (ISSSTA), Aug. 2004, pp. 174–178.

42] J. Armstrong and H. A. Suraweera, “Decision-directed impulse noise mitigation for OFDM in frequency selective fading channels [DVB-T example],” in Proc. GLOBECOM IEEE Global Telecommun. Conf. (GLOBECOM), Nov. 2004, pp. 3536–3540.

43] K. Al-Mawali, A. Z. Sadik, and Z. M. Hussain, “Joint time-domain/frequency-domain impulsive noise reduction in OFDM based power line communications,” in Australas. Telecommun. Networks Appl. Conf. (ATNAC), Dec. 2008, pp. 138–142.

44] T. Hirakawa, M. Fujii, M. Itami, and K. Boh, “Improving influence of impulse noise to OFDM signal by recovering time domain samples,” in Proc. Dig. Tech. Int. Conf. Consum. Electron. (ICCE), Jan. 2006, pp. 327–328.

45] A. Mengi and A. J. H. Vinck, “Successive impulsive noise suppression in OFDM,” in Proc. IEEE Int. Symp. Power Line Commun. Appl. (ISPLC), Mar. 2010, pp. 33–37.

46] C. Yih, “Iterative interference cancellation for OFDM signals with blanking nonlinearity in impulsive noise channels,” IEEE Signal Proc. Lett., vol. 19, no. 3, pp. 147–150, Mar. 2012.

47] L. Lampe, “Bursty impulse noise detection by compressed sensing,” in Proc. IEEE Int. Symp. Power Line Commun. Appl. (ISPLC), Apr. 2011, pp. 29–34.

48] T. Y. Al-Naffouri, A. A. Quadeer, and G. Caire, “Impulse noise estimation and removal for OFDM systems,” IEEE Trans. Consum. Electron., vol. 62, no. 3, pp. 976–989, Mar. 2014.

49] X. Jiang, Z. Pang, M. Zhan, D. Dzung, M. Luvisotto, and C. Fischione, “Packet detection by single OFDM symbol in URLLC for critical industrial control: A realistic study,” IEEE J. Sel. Areas Commun., vol. 37, no. 4, pp. 933–946, Feb. 2019.

50] M. Zhan, Z. Pang, M. Xiao, M. Luvisotto, and D. Dzung, “Wireless high-performance communications: Improving effectiveness and creating ultrahigh reliability with channel coding,” IEEE Ind. Electron. Mag., vol. 12, no. 3, pp. 32–37, Sept. 2018.

51] C. Berrou, A. Glavieux, and P. Thitimajshima, “Near Shannon limit error correcting coding and decoding: Turbo-codes,” in Proc. IEEE Int. Conf. Commun. (ICC), May 1993, pp. 1064–1070.

52] E. Zehavi, “8-PSK trellis codes for a Rayleigh channel,” IEEE Trans. Commun., vol. 40, no. 5, pp. 873–884, May 1992.

53] J. H. Siegel, L. B. Milstein, “Performance analysis and code optimization of low-density parity-check codes on Rayleigh fading channels,” IEEE J. Sel. Areas Commun., vol. 19, no. 5, p. 924–934, May 2001.

54] Y. Hori and H. Ochiai, “Performance analysis and interleaver structure optimization for short-frame BICM-OFDM systems,” IEEE Trans. Wirel. Commun., vol. 15, no. 1, pp. 651–662, Jan. 2016.

55] S. Y. L. Goff, B. S. Sharif, and S. A. Jimaa, “Bit-interleaved turbo-coded modulation using multiuser spreading coding,” IEEE Commun. Lett., vol. 9, no. 3, pp. 246–248, Mar. 2005.

56] S. Hong, S. Kim, D. Shin, and I. Lee, “Quasi-cyclic low-density parity-check codes for space-time bit-interleaved coded modulation,” IEEE Commun. Lett., vol. 12, no. 10, pp. 767–769, Oct. 2008.

57] D. S. Yoo, W. E. Stark, K. P. Yar, and S. J. Oh, “Coding and modulation for short packet transmission,” IEEE Trans. Veh. Technol., vol. 59, no. 4, pp. 2104–2109, May 2010.

58] H. Gerlach-Erhardt, “Real-time requirements in industrial automation,” ETSI Wireless Factory Starter Group, Oct. 2009.
Ming Zhan (M’17) received the master’s degree in communication and information systems from Southwest Jiaotong University, Chengdu, China, in 2004, and the Ph.D. degree from the National Key Laboratory of Science and Technology on Communication, University of Electronic Science and Technology of China, Chengdu in 2013. From 2016 to 2017, he worked as a Visiting Scholar with the Royal Institute of Technology, Stockholm, Sweden, and the ABB Corporate Research Center, Västerås, Sweden. He is currently a Professor with the School of Electronics and Information Engineering, Taizhou University, Taizhou, Zhejiang, China. His research interests include low-complexity and energy-efficient error correction decoders, wireless sensor networks, and high-performance wireless communications in industrial automation.

Zhbo Pang (M’13, SM’15) received MBA in Innovation and Growth from University of Turku in 2012 and PhD in Electronic and Computer Systems from the Royal Institute of Technology (KTH) in 2013. He is currently a Senior Principal Scientist at ABB Corporate Research Sweden, and Adjunct Professor at the University of Sydney and the Royal Institute of Technology (KTH). He is a Senior Member of IEEE and Co-Chair of the Technical Committee on Industrial Informatics. He is Associate Editor of IEEE TII, IEEE JBHI, and IEEE JESTIE. He was General Chair of IEEE ES2017 and General Co-Chair of IEEE WFCS2021 and Invited Speaker at the Gordon Research Conference AHI2018. He was awarded the “Inventor of the Year Award” by ABB Corporate Research Sweden, three times in 2016, 2018, and 2021 respectively. He works on enabling technologies in communication, computing, and machine intelligence for Industry 4.0 and Healthcare 4.0.

Dae Fey Dzung (M’79, LM’2017) received the M. Sc. and Ph. D. degrees in electrical engineering from the Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, in 1975 and 1981, respectively. He has been with Brown-Boveri, Baden, Switzerland, Alcatel, Zürich, Ascom, Maegenwil, Switzerland, and Bosch Telecom, Maegenwil. He was involved in 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 cybersecurity issues in industrial and utility communication systems. Since 1997, he has been with the ABB Corporate Research Center, Baden, Switzerland, where he was an ABB Corporate Research Fellow in Industrial and Utility Communication. His current technical interests include communication networks for factory automation, process automation, and the smart grid, especially networks using heterogeneous technologies such as wireless and powerline communications.

Kan Yu (M’16) received the Bachelor of Engineering degree in communication engineering from the Beijing University of Posts and Telecommunications, Beijing, China, in 2005, the Master of Engineering degree in communication engineering from the Chalmers University of Technology, Göteborg, Sweden, in 2010, and the Ph.D. degree from Malardalen University, Västerås, Sweden, in 2014. From 2005 to 2008, he worked as a Telecom Software Engineer with Datang Telecom and Huawei Beijing Research Institute. From 2016 to 2018, he worked as an RF Engineer with Huawei Sydney. In 2015, he was a Visiting Researcher with the University of Sydney. Since August 2018, he has been a Lecturer in the Internet of Things with the Department of Computer Science and Information Technology, La Trobe University, Australia. His current research interests include the Industrial Internet of Things, reliable and low-latency industrial wireless communications, and real-time industrial communications. He received the Best Paper Finalist at the IEEE International Symposium on Industrial Electronics in 2012 and the Best Paper Award at the International Conference on Information Technology in 2014. He received the Hans Werthen Grant from the Royal Swedish Academy of Engineering Science (IVA) in 2015 and The Ericsson Research Foundation Grant from Ericsson in 2015 and 2016.

Ming Xiao (SM’11) received the bachelor’s and master’s degrees in engineering from the University of Electronic Science and Technology of China, Chengdu, in 1997 and 2002, respectively, and the Ph.D. degree in telecommunication theory from the Chalmers University of Technology, Göteborg, Sweden, in 2007.

From 1997 to 1999, he worked as a Network and Software Engineer at ChinaTelecom, Beijing, China. From 2000 to 2002, he also held an administrative position with the Sichuan Communications, Chengdu. Since 2007, he has been with the School of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden, where he is currently an Associate Professor in Communications Theory.

He was the recipient of Best Paper Awards at the International Conference on Wireless Communications and Signal Processing in 2010 and the IEEE International Conference on Computer Communication Networks in 2011. He was also the recipient of the Chinese Government Award for Outstanding Self-Financed Students Studying Abroad in 2007, the Hans Werthen Grant from the Royal Swedish Academy of Engineering Science (IVA) in 2006, and Ericsson Research Funding from Ericsson in 2010. Since 2012, he has been an Associate Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE COMMUNICATIONS LETTERS (Senior Editor since 2015), and IEEE WIRELESS COMMUNICATIONS LETTERS.