Spectrum-Efficient Analog Pulse Index Modulation for High-Volume Wireless Data Telemetry

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***Abstract*—Spectrum-efficient, high-density, and high-speed data transmission are essential to store and exchange sensitive information through Internet-of-Things (IoT) networks. However, the resource-constrained IoT devices and the limited existing frequency spectrum pose a significant challenge to employing the more efficient technique for the next-generation technology. This paper presents an innovative pulse index modulation (PIM) architecture with a randomization technique for analog pulse-based packet-less high-volume data transmission. The pulse-based compression simplifies the encoding and decoding schemes for short-range wireless telemetry. The pulse randomization technique creates the pulse blinding by reordering the pulse positions and adds an extra level of physical layer security. This paper describes the design, simulation, and prototype development of PIM to validate the feasibility and compatibility of pulse-based data telemetry using the standard architecture. Simulation results show that the proposed PIM increases the data compression ratio by 2.61 times and improves the processing time by 5.56 time compared to the Huffman coding for a 3-bit system. Test results show that the BER is $\sim$7.5$\times10^{-4}$ at 10.0 dB SNR, which satisfies the lower bound for data communication and increases the transmission speed k-times by supporting $2^k * k$ bits data using 2^k number of pulses, where k is a non-negative integer number. The proposed PIM has the potential to improve data rate with added security to support the next-generation IoT networks.**

***Index Terms*—Spectrum-efficient, pulse index modulation, data compression, data rate improvements, secure transmission, and short-range wireless telemetry, Cyber-physical system.**

I. INTRODUCTION

Proliferation of wireless sensor technology has transformed different sectors, including healthcare, the agricultural field, military activities, e-commerce, and transportation. The next generation of wireless technology has enabled the possibility of connecting everything under the same networks. It is estimated that more than 41.0 billion IoT devices will be connected to the existing networks by 2027 [1]. Ericson also predicts that the rapidly expanding 5G availability will continue IoT growth [6]. The rapid growth of IoT devices has generated a bulk amount of data and created network congestion on the limited bandwidth. The existing spectrum is inefficient to accommodate 1,000-fold more IoT devices [2]. The exploration of IoT devices brought new challenges, including data transmission bottlenecks, time latency, spectrum unavailability, and security [2].

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Security solutions are essential in short-range wireless telemetry to provide data confidentiality, integrity, availability of service, and prevent unauthorized access. The well-known cryptographic encryption techniques are deployed to provide security and data privacy, but they are involved with key generation, and management complexity that makes them unsuitable for resource-limited IoT devices [19], [20]. A chaotic pulse position modulation security has been reported using a packet-less pulse-based data communication to leverage chaotic signal abstractions [23]. Typically, chaotic modulation leads to better security by removing the periodicity in the signal and adding more randomness to modulate the data symbols. The index reordering technique is developed for secure distance measurement among two trusted devices [24]. The non-volatile Ferroelectric Random Access Memory (FRAM) and Magnetoresistive Random Access Memory (MRAM)-based random numbers provide higher randomness and more robust values [18]. In our prior work, the latency-based True Random Number Generator is presented to secure data transmission for IoT applications [18].

The resource-constraint IoT devices also pose significant challenges due to the limitations of speed, memory, and feature size that create the network burden [3]. The demands of next-generation technology include higher bandwidth, improved data transmission rate, large-volume data transmission, simultaneous connectivity of 1×10^6 connections per 1.0 km area, latency below 1.0 ms, and data reliability and security. The existing infrastructure of wireless telemetry does not support the continuous expansion of IoT devices while simultaneously transferring multiple sensor data, higher computational power, and resiliency to reliable transmission. The existing technologies also require more and better functionalities, lower transmitting power, and spectrum sharing to maximize the network capacity. A new spectrum-efficient (SE) data modulation technique is reported to meet the requirements of advanced high-density IoT netorks [4].

In recent years, several modulations techniques have been developed to support high-density IoT devices. Index modulation (IM) is one of them. It has emerged as a promising technique to meet the demands of high-volume data transmission for next-generation IoT networks. The IM techniques rely on either the physical resources, including antennas, frequency sub-/carriers, or the virtual building blocks, including signal constellation, antenna activation order, and space-time matrix [5]. The orthogonal frequency division multiplexing (OFDM) is a higher order IM technique that relocates the symbols in active sub-carriers to support higher SE with improved performance compared to the classical OFDM technique [6]. The orthogonal code generation in code division multiple

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access (CDMA) also used IM techniques for energy efficient (EE) and SE data transmission with better error performance [7]. However, OFDM and CDMA systems already used the IM for SE wideband wireless transmission with higher throughput and better BER, but the system complexities, including FFT and IFFT computations, are relatively high compared to analog communication [7].

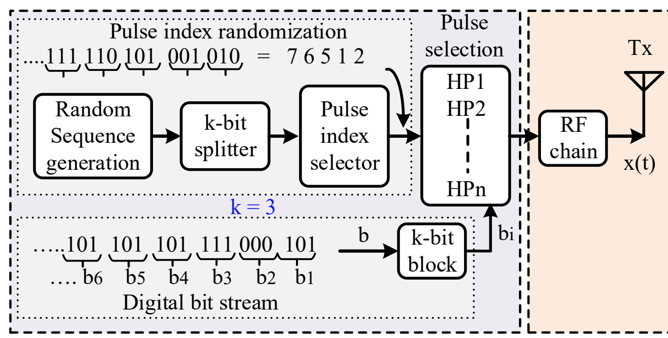
The narrow-width analog pulse signal has been introduced to transmit packet-less data symbolically through a wideband RF antenna for low-power wireless telemetry [8]–[13]. The time-frequency lattice structure carries more than one symbol per grid to increase the data rate n-times using the toroidal waveform-based OFDM technique [10], [11]. Similarly, the Hermite-Gaussian pulse increases the data rate by (n+1) times using superimposed n^{th} order orthogonal pulses [14] and combines over one pulse owing to the signal orthogonality for multi-bit transmission [16]. Many pulse-shaping techniques also have been developed to encode the data bits using a group of symbols for SE wireless communication. However, the pulse energy is dispersed into other sub-carriers in pulse shaping techniques with channel dispersion [15]. The prolate spheroidal wave functions are used to design a time-frequency division multiplexing (TFDM) system for multiple users' applications to avoid pulse energy dispersion [9]. However, inter-symbol interference and inter-carrier interference are the main issues in the TFDM system. Most recently, a novel PIM has been proposed that activates specific pulse shapes according to the incoming transmission bits. It can generate the transmitted pulses like OFDM-IM without the FFT and IFFT computations. However, the main drawback is more than one pulse requires transmitting multi-bit data for SE wireless transmission in IoT applications. [16].

Several works have been reported on SE wireless data transmission; however, they all have pros and cons and focused on either data security or efficient telemetry only [19]–[24]. Therefore, a new design and development will require innovative principles and solutions for effective and efficient wireless data telemetry to meet the demands of next-generation IoT networks. This paper presents an innovative and efficient PIM architecture for analog pulse-based short-range wireless secure data telemetry, where a single-order orthogonal pulse carries multi-bit data. The significant contributions of this work include simplifying the data compression, decompression, and time synchronization schemes for analog pulse-based multi-bit transmission. The pulse randomization technique increases data security by creating pulse position randomness and ambiguity. A prototype test platform is developed to validate the feasibility and compatibility of the proposed PIM scheme.

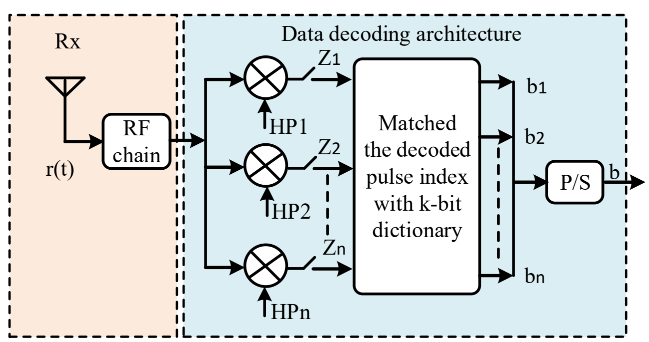
The rest of the paper is organized as follows. Section II describes the analog pulse transmission system architecture and the proposed PIM-based data encoding. Sections III and IV present the security analysis and the performance of the PIM for short-range wireless telemetry, respectively. Section V shows the test setup and measurement results, and finally, the paper concludes in section VI.

II. Proposed Spectrum Efficient Data Telemetry

Fig. 1 shows the schematic diagram of a generic pulse-based wireless transceiver module. It has two main components, the RF transmitter, Tx, to transmit the bitstream symbolically, and a matching RF receiver, Rx, to decode the transmitted data bits. The multi-order analog pulse set is generated using the simple mathematical model described in detail [17]. The generated pulse information is stored in a micro-controller flash memory to implement the data encoding algorithm. In the Tx, a $2^k * k$ bits random number is also generated by the memory-based random number generation technique and divided by a k-bit splitter, where each k-bit represents the index of the distinct pulse signal. The information data bits are divided into k-bit small sub-blocks and encoded by a single pulse among 2^k pulses. The pulse selector determines the memory storage pulse indices that represent the k-bit data symbolically. Finally, the data-encoded pulse train passes through the RF chain for transmitting through the Tx antenna. The Rx antenna sequentially collects the transmitted pulse pattern, reconstructs and maps the pulse symbols into a binary bitstream. First, the received signal passes through the RF chain, and then through the n-branch-matched filtering blocks to correlate with the template signals. If the received pulse matches with the template signal, the corresponding pulse index is searched in the lookup table to decode the transmitted bits.



(a)



(b)

Fig. 1. Transceiver block diagram of PIM scheme (a) Transmitter (b) Receiver.

A. Analog Pulse Generation

The two partial differential equations of the Hermite pulse generator are adopted from previous work described in detail [17]. The modified Hermite function comprises equations 1 and 2, where τ is the time scale factor, and h_n is the n^{th} order Hermite variable. Fig. 2 shows the Simulink model of the simplified AOP generator. It has several benefits including, architecture simplicity, both narrowband (NB) and ultra-wideband (UWB) pulse generation, and EE compared to other Hermite-Gaussian pulse generators. It consists of two integrators, five multipliers, three adders, and a ramp signal that simplifies the architecture significantly. A Sawtooth wave of magnitude $\pm$ 5.0 mV with a 2.0 μs time window is used to substitute the time function and τ = 0.1 μs to generate a width of 2.0 μs multi-order MHPs. The pulse response of h_n and $h_{(n-1)}$ represents the current and previous order pulses.

$$\tau \dot{h_n}(t) = -\frac{t}{2\tau}h_n(t) + nh_{n-1}(t) \quad (1)$$

$$\tau \dot{h}_{n-1}(t) = \frac{t}{2\tau}h_{n-1}(t) - h_n(t) \quad (2)$$

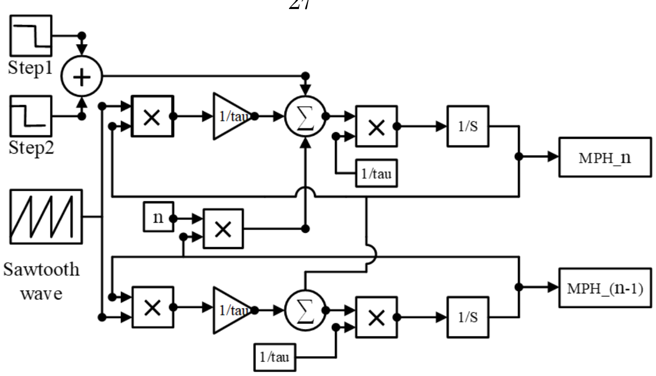


Fig. 2. Simulink block diagram of the MHP set generator.

B. Pulse Index Modulation

The main goal of this paper is to design and implement the k-bit encoding with data security using the analog pulse-style packet-less communication paradigm. It is also leveraged the data density by supporting multi-bit encoding using distinct analog pulses. A data unit protocol is constructed using a separate pulse signal whose index number is modulated based on the randomization encoding template. This modulation type removes the pulse signal's periodicity and adds more randomness to the data symbol, ensuring better security and privacy. The memory-based TRNG scheme modulates the pulse index after threshold time, T_K sec interval to prevent the data-coded pulse positions from the hackers/attackers. The combination of analog pulse-based k-bit encoding and the randomization technique has the potential to provide a SE and EE architecture for resource-constraint IoT networks.

Fig. 3(a) shows the architecture of the PIM using serial-serial data transmission by an analog pulse of width, T_s μs, where a distinct order pulse carries k-bit data. The baseline of the PIM contains a start pulse, i.e., sync pulse of width, T_p at the beginning of the transmitted pulse train to identify the starting point of k-bit encoding. The time gap between two identical consecutive sync pulses symbolically represents the transmitted data bits. Figs. 3(b) and (c) illustrate the conventional single pulse system and the proposed PIM scheme, respectively. The OOK techniques encode the data bit by a single pulse, whereas the proposed PIM scheme encodes k-bit data by distinct order pulses.

The MHPs and SMHPs show the distinct order of 0° and 180° phase-shifted analog pulses. The pulse symbols MHP_0

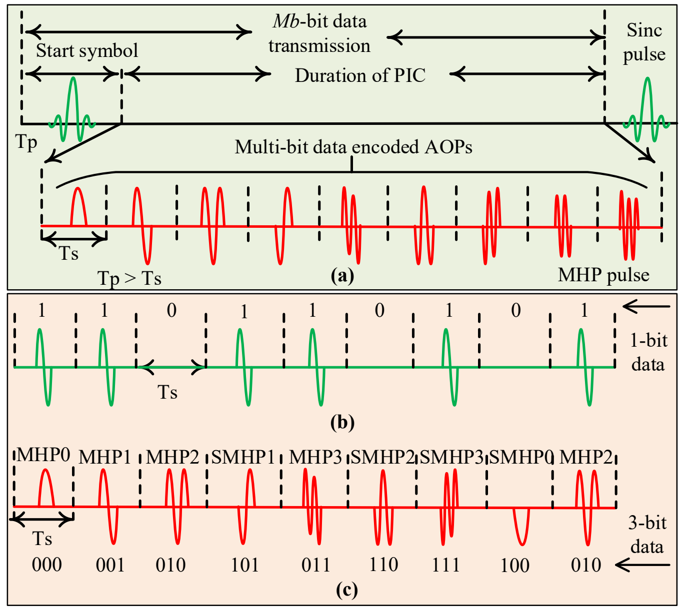


Fig. 3. Data modulation scheme (a) proposed PIM encoding architecture, (b) conventional single pulse system, and (c) k-bit encoding (k = 3).

to MHP_3 depict the zero to third-order pulses, respectively with a constant time window of δ = T_s. Typically, the δ is in nano/pico second for high-speed data transmission. In resource-constraint wireless telemetry, power saving is also a crucial consideration in delivering a large amount of time-series data. The compression technique reduces the transmission energy by compressing a large volume of data. The proposed PIM is a direct method to compress data volume symbolically. It is an efficient approach for saving computing power and time. It also reduces the data size by k-bit using a single pulse and allows transmitting data with a very low-energy budget in terms of few pulses compared to the conventional compression algorithm or sophisticated digital signal processing. The total number of pulses, N_p = 2^k depends on the value of k-bit encoding.

The proposed data encoding scheme involves several steps. These steps are described in chronological order below.

Step 1: Divide the information bitstream into small data series of equal size based on the length of the transmitted data frame. The data length is n times M_b-bit, where n is an integer number and M_b = (k-bit $\times$ N_p) bits. Here, N_p is the number of analog pulses.

Step 2: Apply the k-bit data encoding to each small series of bits, where each pulse index represents k-bit data.

Step 3: For each small group of the bitstream, the pulse-coded information transmits sequentially from the memory storage pulses according to the index number.

Step 4: Add a start indicator i.e., sync pulse at the front of the pulse-coded pattern to identify the starting point.

Step 5: For multi-user applications, a single order pulse and their time-shifted (20% to 70% [25]) pulses will be used to encode each group of M_b bits of data.

C. Pulse Randomization Techniques

An attacker always tries to search the existing vulnerabilities at the different layers of communication networks. He/she attempts to access secret information transmitted through wireless media. If the hacker gets access to the transmitting information, then they can manipulate the bits by changing the intrinsic signal characteristics i.e., the pulse shape, amplitude, and time interval of the arriving signal. The pulse randomization technique prevents physical attacks that require the attacker to know the shape of the pulse. The pulse randomization technique randomized the data-encoded pulse index according to the customized Fisher-Yates shuffle algorithm with a random key K_i. To encode M_b bits of data, the required number of pulses is N_p, including the original and shifted pulses. The random key (K_i) determines the sequence of the randomized pulse index. The same algorithm is required in decoding to retrieve the transmitted pulse index.

Initial pulse index

Index	AOP set	3-bit data
1	MHP0	0 0 0
2	MHP1	0 0 1
3	MHP2	0 1 0
4	MHP3	0 1 1
5	SMHP0	1 0 0
6	SMHP1	1 0 1
7	SMHP2	1 1 0
8	SMHP3	1 1 1

(i)

Index randomization at 'T_h' Sec.

Index	AOP set	3-bit data
1	SMHP0	0 0 0
2	MHP2	0 0 1
3	SMHP3	0 1 0
4	MHP1	0 1 1
5	MHP3	1 0 0
6	SMHP2	1 0 1
7	MHP0	1 1 0
8	SMHP1	1 1 1

(ii) ......

Index randomization at 'n*T_h' Sec.

Index	AOP set	3-bit data
1	MHP3	0 0 0
2	SMHP1	0 0 1
3	MHP0	0 1 0
4	SMHP0	0 1 1
5	MHP1	1 0 0
6	SMHP2	1 0 1
7	MHP2	1 1 0
8	SMHP3	1 1 1

(n)

Fig. 4. Pulse randomization architecture (i) initial pulse dictionary, (ii) index randomization at T_h sec., and (n) randomization dictionary at n*T_h sec.

Fig. 4 shows the pulse index randomization (PIR) based on k-bit modulation architecture. In the proposed scheme, the pulse index is changed randomly after time, T_h sec to encode the information bits according to the k-bit dictionary. The same pulse index does not always indicate the same k-bit data in the PIR technique. Assume that the MHP_2 signal's index number 3 represents "010" bits and is transmitted symbolically in the first T_h sec (Fig. 4(i)). After T_h sec, the pulse randomization technique changes the index randomly based on the k-bit random number. Assume the new index number 9 of MHP_2 represents "100" bits instead of "010" bits (Fig. 4(ii)). Similarly, the pulse index of all the distinct N_p pulses changes randomly and encodes the bitstream with a new encoding template. Since the random key changes periodically (T_h sec) and the index number of the distinct pulses also varies, that creates a pulse blinding to third parties. Therefore, the PIR scheme maintains data privacy and keeps it hidden from an adversary for secure data transmission.

III. Security Analysis

The proposed PIM encodes the binary combination of k-bit data. The distinct order pulses are used to distinguish the binary combinations of the k-bit data. In this paper, the security level is increased by adding the randomness of the data-encoded pulse index. This section describes the data security enhancement by the proposed PIM based on the analysis of the threat model and pulse randomization.

1) Threat Model: Let us assume a scenario where the sensor node transmits data to a local server. The sensor node and the local server have a shared secret and access to commonly used network standards and protocols. The hacker's primary aim is to hack the communication channel and breach data privacy. They have different intentions of performing security breaches for obtaining channel access, manipulating the source information, stealing data, and diverting the transmission channels. In this paper, the man-in-the-middle attack is considered as the threat model to explain secure data communication. It is assumed that the attacker always tries to intercept and read the transmitted message, not manipulate it. They also know the procedure of pulse set generation schemes, k-bit data encoding using analog pulses, and random number generation techniques. The hacker is also familiar with how to decode the message information from the symbolical representation of the transmitted pulses. However, they do not know the exact random pulse sequence, and they will go through a brute-force approach to decode the transmitted data.

2) Securing Channels with Randomized Pulses: The pulse randomization technique can prevent physical attacks by using the narrow pulse width signal. The cryptographic pulse blinding technique requires the attacker to know the shape of the pulse symbols to decode the transmitted information. However, the attacker does not know which pulse belongs to which k-bit data by randomizing the pulse index. Table: I represents the scenario of the proposed technique based on the information about the average time required for the exhaustive key search [26]. The total number of combinations of N_p pulse is $N_p!$. The larger value of N_p shows better data security based on the average time required for an exhaustive key search. According to [26], the expected number of trials to get the correct combination is half of the total number of combinations. The time required for cracking the key also depends on the speed of the attacker's computer.

TABLE I
Average time required for exhaustive key search

Number of bits, k	Number of pulse, N_p=2^k	Number of possible combinations, N = N_p!	Time required at 1.9 GHz processor decode/sec	Time required at 2.9 GHz processor decode/sec
2	4	24	6.31×10^{-9}	4.13×10^{-9}
3	8	4.03×10^{4}	10.60×10^{-6}	6.94×10^{-6}
4	16	2.09×10^{13}	3.81 hours	2.50 hours
5	32	2.63×10^{35}	2.19×10^{18} years	1.43×10^{15} years

Table I shows a total of 8 and 16 distinct analog pulses are required to encode the 3-bit and 4-bit data, respectively. The 4-bit encoding scheme has a total of 2.09×10^{13} possible combinations of the pulses. The time of re-randomizing the pulse encoding template should be selected considering the attacker's 1.9 GHz processor computer at $T_h \leq 3.81\ hours$ and $T_h \leq 2.50\ hours$ for 2.9 GHz processor. If 32 pulses are used to map 5-bit data, then it would require about 2.19×10^{18} and 1.43×10^{15} years, respectively which are virtually impossible. The higher-bit encoding creates more randomness that requires a large amount of time to decode the information bits by brute-force methods. But, the onboard memory storage of IoT devices limits the number of high-bit encodings using the PIM techniques. To ensure security, the threshold level of pulse randomization time, T_h sec should be updated according to Table I. The new random number generates in every T_h sec interval creates randomness and ambiguity for the hacker to enhance the security level.

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The short-width analog pulse reordering is a new modulation technique that enhances the extended mode of IEEE 82.15.4f with cryptographic operations at the pulse level to prevent physical layer attacks, including the early detection and late commit (ED/LC) attack [24]. Pulse reordering ensures low-level data security where existing cryptographic security may not be possible and requires maintaining data privacy in short-range wireless telemetry. Since a successful ED/LC attack is based on the attacker knowing the pulse amplitude, time interval, and pulse starts and ends point, the PIR technique prevents this type of attack by blinding the pulse positions. The pulse blinding is suitable for resource-constraint applications, where the secure keys generation and management is difficult and require data privacy. Therefore, the PIR technique adds low-level physical layer security with data compression for short-range telemetry to meet the demands of next-generation IoT networks.

IV. Performance Analysis of the PIM Scheme

The performance of proposed data encoding algorithm is developed and simulated in MATLAB to validate the k-bit encoding using an analog pulse set. In this paper, a 2.0 μs multi-order analog pulses are generated with 1.1 $\pm$ 0.15 MHz half-power bandwidth and contain $\sim$ 450 nJ signal energy.

A. Architectural Simplicity of the Transceiver

The proposed PIM architecture is different from the existing PIMs [16]. In existing PIMs, the multi-bit data is modulated by using two distinct orders of Hermite-Gaussian pulses along with the M-ary mapper. At first, the incoming bits were divided into two sub-blocks. The first two bits were encoded using Hermite-Gaussian pulses by selecting the indices based on the look-up table [16] and the BPSK methods were used to modulate the last two bits of data. Finally, the data encoded pulse was multiplied by the output of the M-ary mapper and superimposed on top of another by time-domain summation. The composite Hermite-Gaussian pulse shows the multi-bit data within a single time window, but it requires two different receiver models, i.e., (i) Matched filter (MF) and (ii) Maximum likelihood (ML) detection schemes to decode the transmitted data bits. On the contrary, the presented encoding scheme in this paper is less complex and straightforward to encode the same number of bits by a single-order analog pulse. The proposed PIM also simplified the transmitter architecture by modulating the k-bit data using a set of memory-based distinct pulses. The correlator-based decoding minimized the computational power to find the transmitted information bits.

B. Spectrum-Efficient Telemetry

The analog pulse set has signal orthogonality, higher bandwidth, and coexistence with other applications by sharing the frequency spectrum. The multi-order pulse contains the same bandwidth and coexists in the composite signal for multi-user applications. For example, the original multi-order pulse signal indicates the different data users and their various time-shifted pulses carry the combinations of k-bit to support multiple users' data [25]. The multi-order analog pulse set contains a

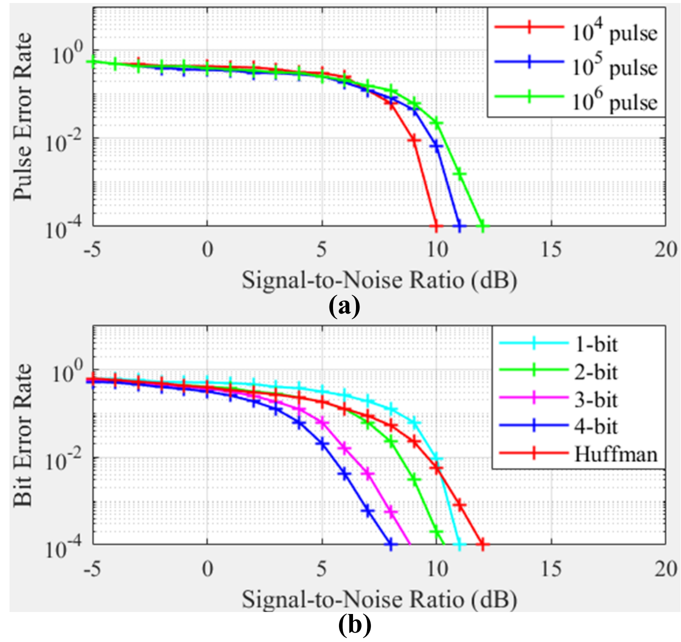

Fig. 5. Simulation results of error rate vs. signal-to-noise ratio at different (a) number of pulse transmission and (b) bit encoding for PIM scheme.

fixed spectrum around 1.1 $\pm$ 0.1 MHz for short-range wireless telemetry in high-density IoT networks. The data transmission rate is 1.5 Mbps for k = 3-bit encoding by a 2.0 μs analog pulse signal. Then the spectral efficiency of the proposed scheme ranges from (1.25 to 1.5) bits/sec/Hz for 2.0 μs pulse set. If the ns or ps pulses are applied for k-bit encoding then the spectral efficiency will be much higher.

C. Pulse and Bit Error Rate Investigation

In this paper, the pulse-error-rate (PER) and the bit-error-rate (BER) of the k-bit encoding are evaluated using MATLAB simulations by varying the SNR levels ranging from -5.0 dB to +15.0 dB. Fig. 5(a) shows the PER for 10 k, 100 k, and 1000 k pulse transmission and reception with AWGN channel noise. In computer simulations, the SNR defines the ratio of energy per symbol to noise power. The simulation results show that the PER increases by increasing the total pulse transmission number. Similarly, the BER is investigated to evaluate the performance of the proposed scheme. Fig. 5(b) shows the BER for a different levels of data bit encoding by a single order analog pulse. This paper has performed the computer simulation for 1-bit, 2-bit, 3-bit, and 4-bit encoding to investigate the effect of error rate with increasing the transmitted k-bits carried by a single pulse. The BER decreases with increasing the number of bits transmitted by single-order pulses, like the M-ary pulse position modulation (PPM) technique. In M-ary PPM, the theoretical relationship between the BER and the SNR is inversely proportional. For the same SNR, a higher number of M results in a lower BER value. The proposed PIM scheme also shows that the BER decreases with increasing the number of bits transmitted by a single analog pulse.

D. Level of Compression Achieved by PIM Scheme

At the sensor node, the data transmission scheme is the main source of energy-saving for high-volume wireless telemetry.

Several research efforts have been made to reduce the energy required for data transmission using different compression techniques. The lossless data compression scheme can reproduce precisely the original transmitted data information by the decompression process. In contrast, lossy data compression can't produce the exact transmitted information. Most of the work focuses on lossless compression with higher precision for high-accuracy applications. The proposed scheme encodes the binary bitstream by PIM, where each pulse carries k-bit data. Therefore, the proposed encoding scheme compressed the data volumes directly by supporting large volume data using 2^k number of distinct pulses. Table II represents the data compression and time latency improvement in the proposed PIM compared to the conventional Huffman data encoding. Test result shows that the proposed PIM is better than the Huffman encoding for multi-bit data modulation using a single order pulse.

TABLE II
DATA COMPRESSION AND TIME LATENCY IMPROVEMENT.

k-bit encoding scheme	Data volume (bits)	Compressed data (Huffman)	Compressed data k-bit	Data compression ratio
3-bit	3000000	2611529	1000000	2.61
4-bit	4000000	3906403	1000000	3.90

k-bit encoding scheme	Data volume (bits)	Elapsed time (sec) (Huffman)	Elapsed time (sec) (k-bit)	Time rate improvement
3-bit	3000000	0.553793	0.099545	5.56
4-bit	4000000	0.582006	0.204550	2.85

E. Data Transmission Rate Improvement

Throughput is one of the most critical requirements to estimate the quality of service in IoT networks. In this paper, the data accuracy is compared with the Huffman coding in terms of BER investigation. The MATLAB simulation package has been performed to check the BER by varying the SNR from -5.0 dB to 20.0 dB. Fig. 5(b) shows the data accuracy comparison between k-bit encoding and Huffman coding. Assume, in k = 3-bit encoding experiment the PIM compressed 3×10^6 bits of binary data to 1×10^6 bits. The compressed bitstream is then encoded according to the pulse encoding template. The additive white Gaussian noise (AWGN) signal is added with the data-encoded pulse train to represent the channel noise. Finally, the correlator-based receiver algorithm decodes the transmitting pulses and converts them to binary bitstream using a prior known template to find the missing information bits.

On the other hand, the Huffman coding compressed the 3×10^6 bits binary data corresponding to 1×10^6 symbols (0 to 7) to 26,11,529 bits. A single-order pulse (MHP1) is used to encode the bitstream using the BPSK method. The BER plot shows that the proposed PIM has better data accuracy than the Huffman coding for transmitting less number of analog pulses. Understandably, Huffman coding requires more pulse transmissions to transmit the same amount of data volume compared to the PIM. It is also noticeable that the BER of single-bit encoding and Huffman coding are identical because they are almost transmitting same amount of pulses. Fig. 5(a) shows that the higher number of pulse transmissions increases BER than the lower number of pulse transmissions.

V. PROTOTYPE DEVELOPMENT AND TEST RESULTS

A prototype test platform is configured to validate the system feasibility and compatibility of analog pulse-based data transmission via wireless media. Fig. 6(a) shows the testbed of the wireless transceiver, where the Tx is on the right, and the Rx is on the left. The Tx and Rx antennas are placed 6.0 feet apart to perform the test. The commercially available customized RF mini-circuit modules with μ-controller board and low-power interfacing circuits are used to build the Tx and Rx sections. In this paper, narrow-band communication is chosen with a constant pulse duration of T_s = 600 μs considering the trade-offs among the hardware limitations, laboratory test facilities, and pulse transmission rate. The clock frequency of the MKR1010 μ-controller board is 48 MHz with a flash memory limitation of 512 kB. The multi-order analog pulses are stored on the SD card, where each signal is comprised of 136 samples and occupied $\sim$ 4.0 kB memory storage for 4-distinct pulses. The Arduino platform is used to create the shifted pulse and implement the encoding algorithm from the memory-based pulse information. The analog out of the μ-controller board is interfaced with the RF chain through low-power mixer driver circuits to verify the feasibility of pulse-based communication.

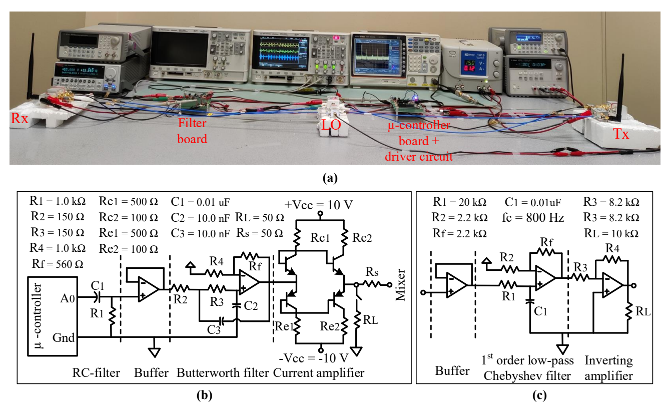

Fig. 6. Test platform (a) prototype development using Mini-circuits RF modules, (b) driver circuits to feed microcontroller signal to RF mixer, and (c) low pass filter to recover the transmitted base band signal.

The serial transmission 'analog out' of the μ-controller board signal shows the data-encoded pulse train, which contains a 0.75 V_{dc} offset and provides insufficient power to drive the RF mixer module (ZX05-1-S+). Thus, a low-power analog circuitry-based driver circuit is designed and developed to drive the RF mixer. Fig. 6(b) shows the configuration of the driver circuit. The interfacing circuit comprises of the DC filter, buffer, level shifter, and current amplifier. First, the RF mixer-1 (ZAD-8+) translates the base-band low-frequency signal to 1.0 MHz with a signal generator signal to meet the RF input requirements of mixer-2 (ZX05-1-S+). The output of mixer-2 is a 500 MHz modulated signal by a local oscillator (ZOS-535+) and amplified by a power amplifier (ZFL-1000B+) before transmitting through the RF antenna (ANT-4WHIP3H-SMA) at band frequency (430 - 470) MHz.

The local oscillator signal feeds to both mixers via RF-splitter (ZESC-2-11+) with an equal length of co-axial cable. All the RF devices and co-axial cables are calibrated via a VNA calibration kit before developing the prototype test platform. At the receiver, the transmitted analog pulse train is received by the RF antenna and passed through the RF chain for signal amplification using a low noise amplifier (ZFL-1000LN+) and frequency down conversion by RF mixer. A low-pass filter (Fig. 6(c)) is also designed to recover the baseband signal.

A. Measurements and Results

The 3-bit encoding is implemented and evaluated through the prototype test platform for validating the PIM using the 500 MHz frequency band. Fig. 7 shows the test results. The green, yellow, and blue traces show the data-encoded pulse train, received signal, and carrier-modulated signal. The transmitted bitstream is first divided into 300 bits per small block of 100 pulses to simplify the signal processing. Then, the 300 bits data frame is encoded by the memory storage multi-order analog pulses as described in subsection II-B. In front of each data-encoded pulse frame (3-bit/pulse), a zero-order pulse signal is added to minimize the time synchronization complexity for decoding the transmitted bitstream. The full length of the oscilloscope window captures the received pulse frame and saves it into a flash drive for offline processing to decode the transmitted bitstream.

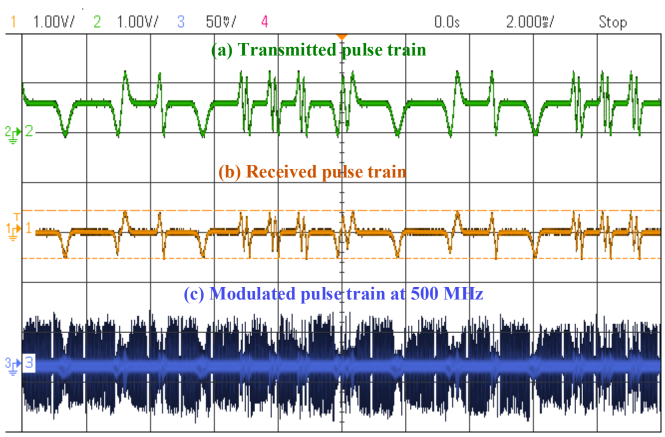

Fig. 7. Test results (a) transmitted pulse train, (b) received pulse train, and (c) modulated pulse train at 500 MHz.

In signal processing, the first step is to find the starting point of the data-encoded pulse frame through indicator pulse detection. Then, the received pulse frame is divided into a 136×100 matrix for 100 pulses based on the sample points of the pulse. The correlation peak is applied to check the correlation sequentially with the memory-based template signal and decode the transmitted data bits. The threshold value of the correlation peak is selected at 0.85 to recover the received pulse. If the peak is higher compared to the threshold value, then the corresponding pulse is presented and printed with the index. Finally, the index number is converted to 3-bit data with the prior known encoding template.

B. BER and PER Investigation

To demonstrate the performance of the proposed techniques, the PER and BER are evaluated under different test conditions. The error rate is calculated by adding the AWGN signal with the test results and varying the SNR from 0.0 dB to 20.0 dB. Fig. 8(a) depicts the PER test results at different pulse frame counts. Test results show that the error rate increases with increasing the frame size of the transmitted pulses, which is the same as the simulation results. The BER is also invested to validate the performance of the proposed scheme. Fig. 8(b) shows the test results of the BER of the proposed scheme. The experimental results experience the reflections from various objects indoor environment, surroundings of electronic devices, reflections from the human body, channel noise, measurement noise, noise added by hardware circuits, and so on. Therefore, the BER is a little bit higher in the test (7.5×10^{-4}) compared to the simulation (1.0×10^{-4}) at ∼10.0 dB SNR for the 3-bit encoding but satisfies the lower bound of the BER for wireless communication.

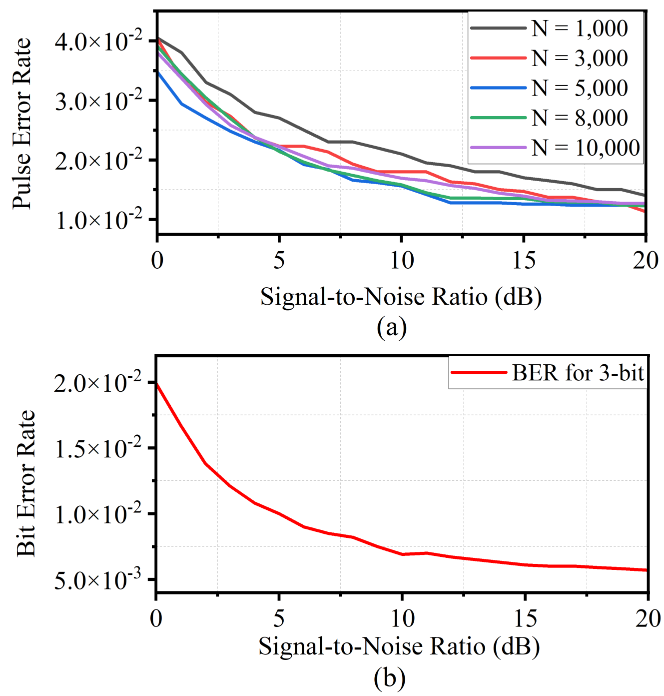

Fig. 8. Experimental results (a) pulse error rate and (b) bit error rate.

C. Summary and Overall Improvement

In summary, the pulse index randomization-based data encoding scheme shows promise in terms of data transmission speed, compression, and data security for low-power and short-range wireless communications. The proposed analog pulse style PIM improved the data transmission speed and data volume by k/T_s Mbps and k$\times2^k$ bits compared to the single pulse systems here, k is an integer number. For instance, in a 3-bit encoding, the data transmission speed is 3.0 Mbps for a 1.0 μs pulse signal. The transmission rate will be 3×100 Gbps for a 1.0 ps. Similarly, the data volume increased by 3×2^3= 24 bits data using 2^3= 8 distinct pulses. Compared to the standard Huffman data compression, the analog pulse-based encoding improved the compression ratio and time latency by 2.61× and 5.56×, respectively (see Table II). In addition, the PIR scheme adds an extra security level by generating random numbers at $\leq T_h$ sec time interval for k-bit encoding.

VI. Conclusion

This paper explores an innovative PIM architecture in the time domain for high-volume sensor data transmission in IoT networks. The multi-bit encoding is presented along with the randomization technique to add extra physical layer security at the transmitter. The correlation peak-based pulse detector is used to simplify the decoding scheme at the receiver. A prototype test platform is configured using the commercially available RF modules with the μ-controller implementation to validate the analog pulse-based communication's performance, feasibility, and compatibility. Simulation results show that the proposed encoding improved the data compression ratio and time latency by 2.61 times and 5.56 times, respectively, compared to the standard Huffman coding. Test results show that the BER satisfied the lower bounds, and it is 7.5×10^{-4} at 10.0 dB SNR for wireless data communication. The proposed analog pulse-based PIM supports $2^k * k$ bits data by 2^k different pulses and ensures the low-level physical layer security, where k is a non-negative integer number. The proposed scheme provides low-power, cost-effective, secure, and scalable data telemetry by changing the k value. Pulse randomization adds low-level security for reliable data transmission in resource constraint IoT applications. Therefore, the proposed scheme will play a critical role in SE short-range data telemetry to meet the demands of next-generation IoT networks.

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