A Multi-bit Data Modulation Using Orthogonal Pulses for High-Density Transmission

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***Abstract*—Analog pulse-based data telemetry is a novel technology that improves data transmission rate for spectrum efficient secure transmission in high-volume wireless sensor applications. However, the analog pulse transmission technology suffers from proper orthogonal pulse generation, data modulation scheme, propagation media, and receiver detection techniques to decode the transmitted bits. This paper introduces a multi-bit data encoding scheme using a set of orthogonal pulses and their time delay factors. The energy-efficient pulse generation technique based on Modified Hermitian Polynomial is used to generate the orthogonal analog pulse set. The proposed analog pulse-based data compression and decompression scheme is validated using MATLAB Simulink packages. The results show that the proposed data modulation scheme increases data transmission rate 1.5×n more compared to single bit transmission, where 'n' is the distinct pulse order, which indicates the number of individual data channels. Therefore, the proposed scheme would be an alternative solution for spectrum efficient wireless data transmission in high-density sensor networks.**

***Index Terms*—Orthogonal pulses, time-shift factor, data encoding, pule elimination, data decoding, WSNs.**

I. Introduction

Short-range data transmission in wireless sensor networks (WSNs) have gained popularity with increasing sensor device deployments and wireless communication technology. The WSNs affects all the sectors of human life, including home to industrial automation, remote patient monitoring, indoor surveillance, security control applications, etc. [1]. A sensor node manifests a micro-controller, data storage, sensor device, analog-to-digital converters (ADC), a data transceiver, etc. Therefore, intelligent sensor-based Internet-of-Things (IoT) devices have the computational capability to control actions and compete with the existing indoor automation. However, the resource-constraint IoT devices suffer from limited memory, computational power, speed, etc. The existing data telemetry also suffers from lower throughput, data integrity, limited frequency spectrum, data channels, and associated cost. Therefore, the proliferation of sensor devices poses significant challenges to WSNs for the aforementioned limitations.

The next-generation networks expect to fulfill the users' escalating demands with the improved data rate, increased channel capacity, effective spectrum utilization of the existing frequency bandwidth (BW), and Quality of Service (QoS). The data rate depends on the used BW and spreading factor. Typically, in the conventional digital data transmission scheme, the chirp spread spectrum technology makes it work well with channel noise, multipath fading, and the Doppler effect, even at low power [2]. There is an inverse relationship between the BW and the spreading factors to increase the data rate. The adequate BW requirements and QoS for voice and video transmission poses challenges in the existing short-range wireless communications. A modulation technique is one way that can enable the adjustment of a signal modulation pattern, which depends on the signal-to-noise ratio (SNR) condition to maintain the stability of the services. However, the number of data channels' usability is limited to a few frequency bands only because of the lack of a continuous frequency spectrum.

The existing digital data transmission technology has several advantages; however it suffers from the sampling rate, A/D and D/A converter, processing time, quantization error, higher BW requirements, etc. Recently, the analog pulse-based data transmission scheme has been proposed both for narrow-band (NB), and Ultra-Wideband (UWB) applications. The analog orthogonal pulses have the signal orthogonality to coexist with other applications. It also removes the D/A conversion for data recovering scheme at the receiver by correlating the received pulse pattern with the known prior encoding templates [3]. In this work, the authors have proposed a novel data encoding scheme using a set of an orthogonal analog pulse set for supporting high-density IoT networks [4], [5]. To increase IoT devices' physical layer security, a randomized analog pulse-based data modulation scheme has been proposed [5]. Though the literature claims that analog pulse-based data modulation scheme indirectly improves the data transmission rate by supporting more data volumes and increases the number of data channels via simulation results for efficient spectrum applications; however, it requires to further study i.e., Bit-Error rate (BER), the investigation of channel effects on analog pulse set for indoor environment.

This paper proposes an analog pulse-based multi-bit data telemetry scheme using a set of orthogonal Modified Hermitian Pulse (MHP). Typically, the pulse-based data transmission system modulates a single data bit by a single pulse; however, in the proposed modulation scheme an individual MHP shows multi-bit data. The modulated data bits are then transmitted symbolically through a wireless medium and the transmitted data bits are recovered by a correlator receiver. The communication channel properties i.e. reflections, fading propagation, interference, affect the analog pulses, including attenuation, distortion, spreading, etc. This paper also investigates the pulse decoding scheme to recover the transmitted pulses of the proposed MHP based data transmission for high-volume sensor applications. The rest of this paper is organized as follows. Section II presents the analog pulse-based data modulation scheme. Section III describes the signal transmission and reception. Section IV and V present the correlator based pulse decoding receiver and simulation results, respectively. Finally, the paper concludes in sections VI with future works.

II. Analog Pulse-Based Modulation Scheme

The analog pulse-based data modulation scheme is a new technology for sensor applications. A set of orthogonal pulses uses to modulate the data-bit and transmit as symbolically. Therefore, the energy-efficient pulse set generation is crucial for the pulse-based data telemetry scheme.

A. Orthogonal Pulse Set Generation

There are different pulse generation schemes for the orthogonal pulse set generation such as, Gaussian function, Haar function, Hermitian polynomial, and modified Hermitian polynomial (MHP) [6], [7], etc. Each pulse generation scheme has its own merits/demerits with implementation limitations. Recent works also suggest different pulse shape techniques to generate orthogonal pulses along with FPGA-based multi-order Hermitian pulse generation [8]. However, the Modified Hermitian polynomial-based pulse set generator is a simplified method among the existing methods [7]. In this article, we generate the NB pulse with a 20 μs pulse width by using τ = 1.0×10^{-6}, the Sawtooth wave function at -5.0 μV to 5.0 μV and time period 2.0 μs (-1.0 μs to 1.0 μs). By varying 'n' to different integers, the pulse responses of two dynamic systems, n^{th} and $(n-1)^{th}$ order derivatives are obtained, which represents the MHPs as shown in Fig. 1.

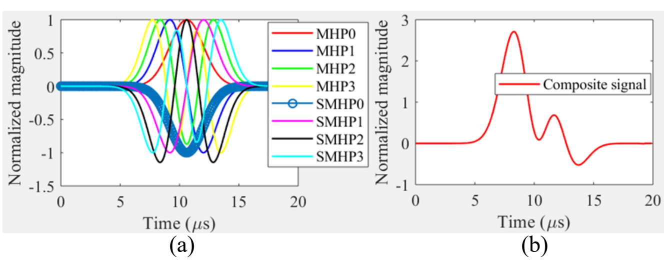


Fig. 1. Different order orthogonal pulse signal with 2.0 us pulse width.

B. Pulse-Based Data Encoding Scheme

Fig. 2 shows the analog pulse-based data encoding scheme, where the digital bits stream modulates by a set of analog orthogonal MHP pulses. In this paper, we proposes 3-bit data encoding scheme for multi-user applications where each single order pulses indicates 3-bit data instead of single bit. The distinct pulse order of MHPs represents the distinct data channels. The time-shifting property of MHPs uses to creates different pulse positions to modulates the digital bitstream. Fig. 2(a) shows the data encoding templates for sensor 1, where the SMHP1 indicates the out of phase of MHP1 pulse signal and represents the '000' data bits. In our previous studies, we have found the lower and upper limit of time-shift factor of MHPs is 20% to maintain the signal orthogonality with original pulse signal. Therefore, the t_1, t_2, t_3, t_4, t_5, and t_6 represents the different time-shift factors i.e., 20%, 30%, 40%, 50%, 60%, and 70%, respectively to encodes the different combinations of 3-bit data as per templates. Similarly, MHP2, MHP3, and MHP4 pulses and their time-shifted pulses will use to modulate the data bits of sensor 2, sensor 3, and sensor 4, respectively. Fig. 2(b) shows the data encoding scheme of multi-user data using orthogonal MHPs at the sensor hub. Since, all the distinct order pulses are orthogonal to each other therefore, at end of encoding scheme all the pulses are super imposed to create a composite pulse signal which indicates the compressed data volume.

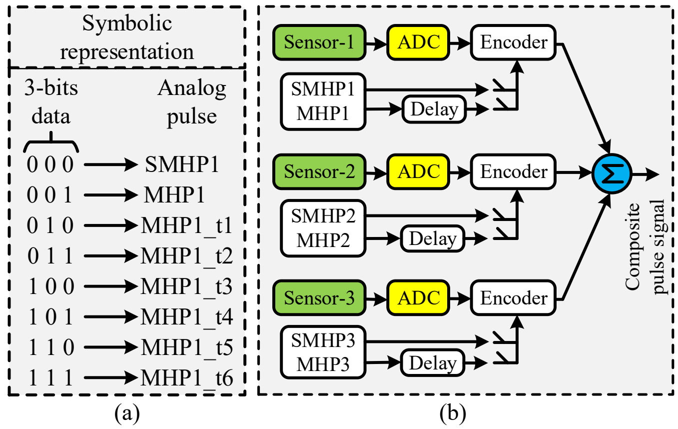


Fig. 2. Pulse-Based data encoding scheme using different orders MHPs.

III. Signal Transmission and Reception

The analog pulse-based transceiver architecture consists of a pulse-based data encoder, signal transmission and reception, and data decoding scheme. Fig. 3 shows the proposed analog pulse-based data telemetry architecture. Each subsection describes briefly as below-

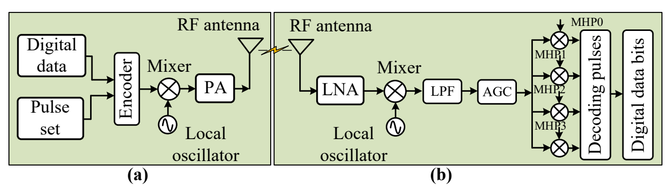


Fig. 3. Analog pulse-based data telemetry architecture.

A. Analog Pulse-Based TX

Fig. 3(a) shows the block diagram of analog pulse-based transmitter. The transmitter (TX) architecture consists of frequency up-converter, signal amplification, and an RF antenna along with data encoder. The multi-order orthogonal MHP set is generated by an energy-efficient pulse generator explained in [7], and stored in a flash memory for further usage. The sensor data modulates by a set of MHPs using PPM techniques as per the templates and translated the composite signal to higher frequency using a sinusoidal carrier. Then the modulated signal amplifies to drive the RF antenna by power amplifier (PA) before to transmit through antenna.

B. Communication Channel

Communication media represents the effects of signal distortion, attenuation, and spreading when traveling through dielectric media. The most critical issue in the analog pulse-based system is the propagation of signals in indoor environments that involves different dielectric material such as wood, bricks, metal, foam, concrete, etc. Typical indoor scenarios, including the LOS, room-to-room, within-the-room, and hallways are considered to investigate the channel effects.

C. Analog Pulse-Based RX

Fig. 3(b) shows the block diagram of the correlator based pulse decoding receiver architecture. First, the received RF signal strength increases to a certain level by LNA for detecting the pulse signal. Then the mixer circuit down converts the received modulated signal by multiplying the same carrier. The base band composite signal then recovered by passing through the LPF and apply the pulse decoding algorithm to decode individual pulses. Finally, the decoded pulses correlate with the known data encoding template to find the missing data after converting to the digital bitstream.

IV. Correlator Based Data Decoding Scheme

Correlator-based pulse elimination scheme is the central part of data decoding in receiver architecture for pulse-based data telemetry. The eliminated pulses then match with the prior known encoding template to find the missing data bits. The decoded pulses can also help to find the missing data channel.

A. Pulse Elimination Techniques

A correlator-based pulse elimination scheme decodes all the individual pulses from the composite pulse signal. The composite signal correlates with the prior know template pulse signal sequentially stored in the receiver flash memory in this scheme. Then check the correlation peak and compare it with a pre-defined threshold. If the respective pulse is presented in the composite signal, its correlation peaks will be higher than the threshold. Then, the corresponding MHP will be eliminated from the composite signal. This pulse elimination scheme will be run parallel to decode all the MHPs in the composite signal. After eliminating all the order distinct time-shifted pulses from the composite signal, the eliminated pulses will match the prior known multi-bit data encoding template for multi-user applications.

B. Data Decoding and Missing Data Bits

Table I shows the analog orthogonal pulse-based 3-bit data encoding template using different time-shifted pulses. Our prior study shows that all the MHPs are orthogonal with their time-shifted pulses. Table I shows the data channel encoding by distinct order orthogonal MHPs. If the decoded pulses are 20% time-shifted MHP1, MHP2, and 50% time-shifted MHP3 in the received composite signal, it indicates 010 001, and 101 data bits come from channel 1, Channel 2, and Channel 3, respectively. The transmitted composite pulse signal transmits 9-bits data as a compressed version via a composite signal. The SMHP represents the 000-bit data. If any specific pulse is missing, it indicates that the corresponding data channel is out of service.

TABLE I
Data encoding template using different time-shifted pulses.

Pulse	t1=0%	t1=20%	t2=30%	t3=40%	t4=50%	t5=60%	t6=70%	t=180%
HP1	001	010	011	100	101	110	111	000

TABLE II
Data channel encoding template using different order pulses.

Channel No.	Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8
Pulse Order	HP0	HP1	HP2	HP3	HP4	HP5	HP6	HP7

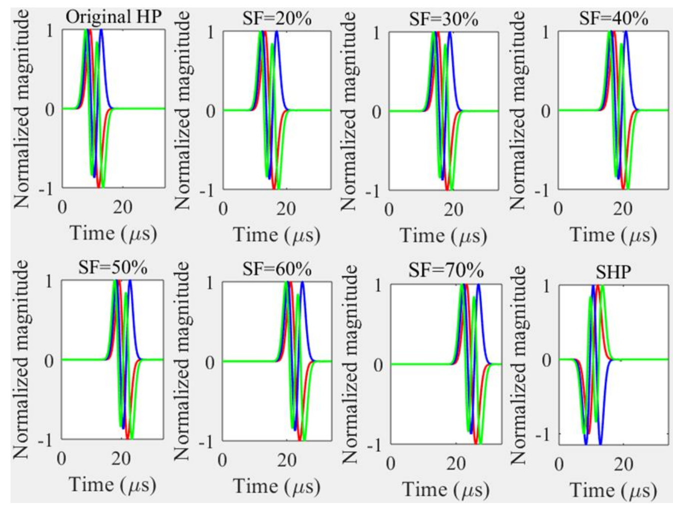


Fig. 4. Different order orthogonal MHPs at various time-shift factors.

V. Simulation Results

This section presents the simulation results that demonstrate the concept analog pulse-based data modulation scheme. The MATLAB simulation tool is used to verify the theoretical idea of the proposed techniques. The simulation results of orthogonal pulse generation, data encoding, and decoding scheme are given, respectively.

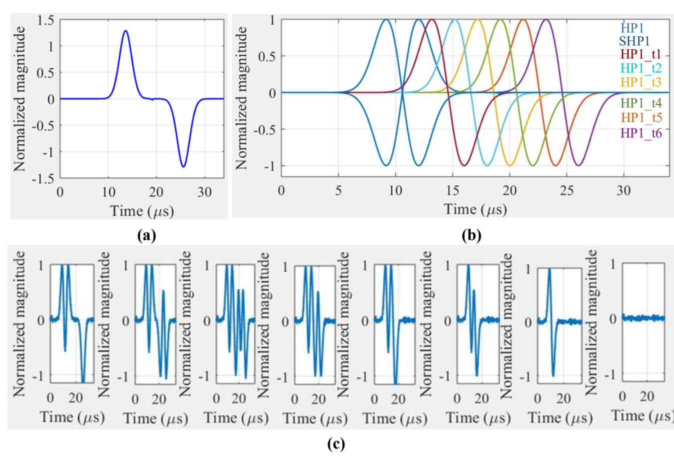


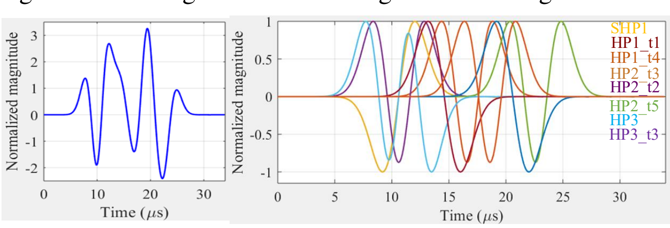
Fig. 5. Simulation results (a) composite signal, (b) decoded pulses from composite signal, and (c) residual signal after each iteration.

A. Orthogonal Shifted Pulse Generation

Fig. 4 shows the orthogonal pulse generation results of different order MHPs. The red, blue, and green trace indicate the first, second, and third-order pulses, MHP1, MHP2, and MHP3, respectively. The pulse width of original multi-order MHPs is 20 μs. To encode multi-bit data, the time-shifted MHP signals are generated by considering different time factors of distinct order MHPs. The pulse width of new data encoding MHPs becomes 34 μs instead of 20 μs. Though the time-shifted orthogonal MHPs initially contain extra time; however, the multi-bit data compression of multi-channel is the overall benefit of the proposed scheme.

B. Single-User Data Decompression

Fig. 5 shows the pulse decompression results for single data channel applications. Fig. 5(a) represents the composite pulse signal comprises MHP1, shifted MHP1 at different time factors, and the out of a phase of MHP1 signal. The composite pulse signal creates with the different time-shifted pulse signals to check the performance of the decoding scheme. A 20 dB Additive white Gaussian noise (AWGN) signal is added with the composite pulse signal to represent the communication channel noise model. Fig. 5(b) shows the different pulse elimination results from the composite pulse signal using the correlator receiver algorithm. In this paper, the cyclic pulse elimination-based pulse decoding scheme decodes all the distinct pulses from the composite signal [3]. Fig. 5(c) shows the residual pulse signal after elimination from the MHP signal corresponding to the highest correlation peak in each iteration. The threshold level of correlation peak (0.20) is used to eliminate all the pulses from the composite signal using correlation peak analysis. It also used this threshold level in parallel correlation checking of a composite signal with the individual pulse signal to decode the transmitted data instantly. Simulation results also indicate all the time-shifted MHP1 signals are orthogonal with the original MHP1 signal.



(a) **(b)**

Fig. 6. Simulation results (a) composite signal and (b) decoded pulses.

C. Multi-User Data Decompression

Fig. 6 shows the simulations results for multi-channel data decompression scheme. In this test, we consider the different sensors data encoded at the sensor hub and transmitted through a communication channel model represented by a 20 dB AWGN. Fig. 6(a) shows the composite signal comprises SMHP1, 20% & 50% time-shifted MHP1 signal, MHP2, 30% & 60% time-shifted of MHP2 signal and MHP3 & 40% time-shifted of MHP3 signal. Fig. 6(b) represents the individual pulse elimination results from the composite signal.

VI. Conclusion

In this paper, an orthogonal MHP based multi-bit data modulation scheme is presented to encode multi-channel data at the sensor hub for high-density wireless sensor applications. The proposed analog pulse-based multi-bit data modulation scheme decodes individual pulses from the composite signal using correlation analysis. It simplifies the data encoding/decoding scheme for multi-channel data transmission symbolically. The MATLAB simulation results indicate that the orthogonal MHP pulse-based multi-bit data transmission scheme will indirectly improve the data transmission rate by supporting multi-channel as a composite signal representing the compressed data volume. The proposed multi-order orthogonal MHPs based data modulation scheme transmits the data volume of 1.5×n bits data as a composite signal, where n is the number of distinct data channels. The proposed data modulation scheme reduces the complexity and D/A converter at the receiver in digital communication. Moreover, the orthogonal pulse-based scheme increases the data transmission speed indirectly by supporting more data channels. The proposed analog MHP-based technology would be a feasible solution for the spectrum-efficient scheme that makes a leading alternative data compression for high-density data transmission in IoT-based 5G networks.

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