A Spectrum-Efficient Data Modulation Scheme for Internet-of-Things Applications

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***Abstract*—With the proliferation of wireless sensor networks, the high-density of sensing data is imposing a significant challenge on spectrum management to share the existing bandwidth. In this paper, a spectrum efficient data encoding scheme is proposed using a set of analog orthogonal modified Hermite pulses. The novelty of this approach is to use an analog pulse-sequence based data encoding scheme, that reduces multi-user interference and supports more data by sharing the same network bandwidth. The serial-parallel data transmission techniques are proposed using a set of distinct pulse sequences instead of a single pulse. The analog pulse set generation and the pulse encoding scheme is analyzed through MATLAB simulation package. Simulation results show that the proposed data encoding scheme will provide 6-times improvement in data rate for 4 distinct orthogonal pulses. The proposed scheme will be a promising feature for high density larger array sensor signal monitoring in a wireless sensor network.**

***Index Terms*—Ultra-wideband communication, signal orthogonality, pulse sequence, composite signal, data transmission rate, and data encoding.**

I. Introduction

The connected devices are increasing exponentially with the inception of the Internet of Things (IoT) and fifth generation (5G) of wireless sensor networks (WSNs). Particularly, the advancement of sensor devices and wireless technology is becoming a more and more pervasive tool for monitoring a wide range of physical phenomena ranging from civil to military applications in IoT networks [1]–[3]. The IoT devices based on 5G network requires a high-speed data transmission with increasing the integration of a large number of recording channels for the real-time monitor, assessment, and control applications. The overall picture of an IoT system with ubiquitous connectivity is shown in Fig. 1. In recent work, both narrowband (NB) and Ultra-Wideband (UWB) schemes have investigated to deal with the resource constraints and the large volume wireless data transmission applications. Each digital signal transmission scheme has its advantages and drawbacks, with limited data rates, higher power consumption, jamming, and a limited number of channels [12], [13], [15], [16]. Out of the various approaches, the analog impulse radio UWB system has widely studied for high data density, low-power, and short-range wireless communication systems [4], [11].

The IR-UWB data transmission system works with relatively large bandwidth. It shows several advantages of supporting high data rate, robustness to multi-path interference, low complexity, low-power consumption and coexistence with other communication systems [5], [12]. Besides this, in IR-UWB system a simple non-coherent energy detection receiver is also required to recover the transmitting data. In the conventional approach, a series of the different pulse train is required for multi-user base stations [11]; otherwise, interference between pulses makes it difficult for proper data reception at the receiver end. On the other hand, orthogonal pulses have the properties to transmit multiple pulses as a composite signal with other pulses simultaneously without any interference. However, the main challenges of the IR-UWB system is the generation of proper orthogonal pulses and their higher-order derivatives. Unlike Haar, Gaussian, and Prolate Spheroidal Wave functions based on pulse generation, the modified Hermite Polynomial shows less computational complexity and constant pulse width [6], [7]. A modified Hermite Polynomials (MHP) pulse set generator with reduced system complexity is reported in [8] for higher-order orthogonal pulse generation.

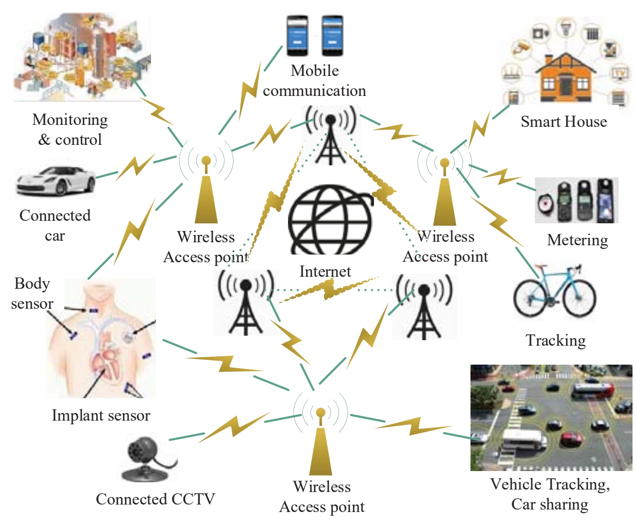


Fig. 1. Schematic overview of an IoT system with ubiquitous connectivity.

In IR-UWB communication systems each data bit is modulated by different pulses and combined them to construct a composite signal. The toroidal waveform based rectangular lattice of the orthogonal frequency division multiplexing (OFDM) technique improves the data rate up to n-times for the n-Hermite pulse system [10]. In the time-frequency lattice

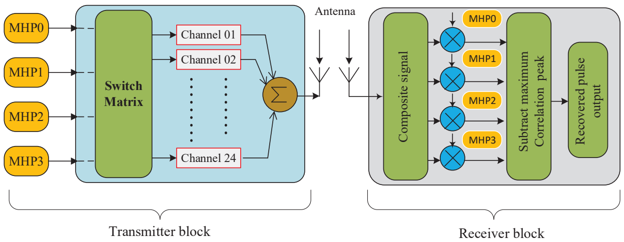


Fig. 2. The functional block diagram of the proposed pulse-encoding scheme based high speed data communication system.

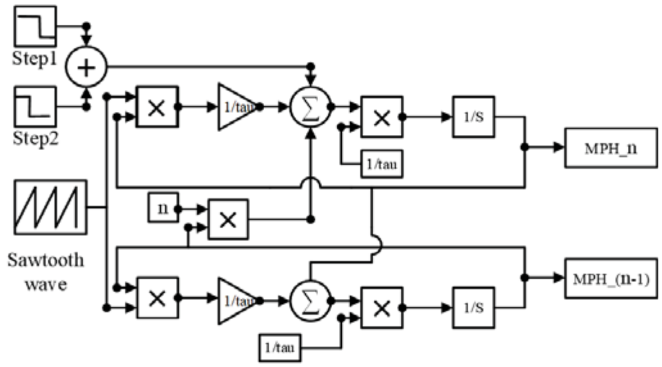


Fig. 3. The Simulink block diagram of the MHP set generator [8].

structure, more than one symbol can be carried by each grid using an orthogonal filter. The superimposed waveform technique proposed the combinations of Hermite-Gaussian functions in each grid to increase the data rate by (n+1) times using n-order orthogonal pulses in the same bandwidth [9]. The data rate improvement is still ongoing research in the IR-UWB system, which is the main contribution in this proposed spectrum efficient high-density data transmission scheme. This data encoding scheme will improve the data transmission rate by supporting (n-1)!-times more data for n-distinct orthogonal pulses.The rest of this paper is organized as follows. Section II describes the system model of the proposed architecture. Section III presents the proposed pulse encoding scheme. Section IV presents the simulation results, and finally concludes the paper in section V.

II. System Model of Proposed UWB Communication

Ultra-wideband communications employ the technique of impulse radio communication that transmitted a very short duration pulses of the order of nanoseconds. Due to these very short duration pulses, the signal occupies extremely large bandwidth and there is no need frequency translation like CDMA, DSSS, FHSS, and OFDM. The IR-UWB system comprises with transmitter, channel, and receiver shown in Fig. 2. The transmitter's prime motive is to convert the data stream into symbols and map these symbols into an analog waveform and transmit by an antenna through air. Media represents the effects of distortion, reflection, and attenuation when traveling through air. The receiver collects the transmitted pulses, reconstructs them and maps symbols into a binary stream. A major challenge is the selection of appropriate modulation techniques when designing the IR-UWB systems. This paper first described the mechanisms and features of the orthogonal Hermite pulse set generation then discussed the proposed pulse encoding scheme with an explanation.

A. Orthogonal Pulse Set Generator

To generate the analog orthogonal pulse the MHP set generator is implemented in Matlab Simulink shown in Fig. 3. This power-efficient simplified model consists of 2-integrators, 5-multipliers, 3-adders, and a ramp signal. The simplified model is designed for sub-GHz UWB communications to produce the MHP pulse set with a pulse width of 20 ns. This small pulse width represents the larger bandwidth of pulse set.

B. Signal Orthogonality Analysis for Different MHPs

The correlation coefficient 'r' is used to compare each MHP pulse with others. The positive and negative value of 'r' represents the stronger positive and stronger negative linear correlation among the pulses. While the zero coefficient factor means there is no linear correlation among them. The coefficient factor 'r' can be found between two signals x, and y by using (1).

$$r = \frac{\sum xy - (\sum x)(\sum y)}{\sqrt{n\sum(x^2) - \sum(x^2)}\sqrt{n\sum(y^2) - \sum(y^2)}} \tag{1}$$

This paper investigates the correlation analysis between different MHP pulses with their composite signal to differentiate each signal from others. The simulation results are given in Table I where, MHP0, MHP1, MHP2, and MHP3 represents the zeroth, first, second, and third-order pulses respectively. The tested results indicate the signal orthogonality. Due to the orthogonal property all MHP pulses are superimposed within same time period to send as a composite signal. It will also help to set the threshold level in receiver to decode all the distinct pulses from composite signal using cyclic pulse elimination approach.

TABLE I
Correlation between the different MHP and their composite signal

	MHP0	MHP1	MHP2	MHP3	Sum of MHPs
MHP0	1.000	0.000	-0.106	0.000	0.293
MHP1	0.000	1.000	0.000	0.000	0.539
MHP2	-0.106	0.000	1.000	0.000	0.452
MHP3	0.000	0.000	0.000	1.000	0.591

III. Proposed Pulse Encoding Scheme

Integrating a large volume of recording channel is a big challenge in the wireless system which causes a substantial growth in data volume into WSN. To achieve high data speed in WSN, the IR-UWB based multichannel system is proposed in this paper. The data encoding scheme is developed based on the properties of orthogonal Hermite pulses. In this proposed

TABLE II

PULSE SEQUENCE SCHEME FOR 4-DIFFERENT ORTHOGONAL PULSES

Seq. No.	TS1	TS2	TS3	TS4	Ch. No.
1	MHP0	MHP1	MHP2	MHP3	1
2	MHP0	MHP1	MHP3	MHP2	2
3	MHP0	MHP2	MHP1	MHP3	3
4	MHP0	MHP2	MHP3	MHP1	4
5	MHP0	MHP3	MHP2	MHP1	5
6	MHP0	MHP3	MHP1	MHP2	6
7	MHP1	MHP0	MHP2	MHP3	7
8	MHP1	MHP0	MHP3	MHP2	8
9	MHP1	MHP2	MHP0	MHP3	9
10	MHP1	MHP2	MHP3	MHP0	10
11	MHP1	MHP3	MHP2	MHP0	11
12	MHP1	MHP3	MHP0	MHP2	12
13	MHP2	MHP0	MHP1	MHP3	13
14	MHP2	MHP0	MHP3	MHP1	14
15	MHP2	MHP1	MHP0	MHP3	15
16	MHP2	MHP1	MHP3	MHP0	16
17	MHP2	MHP3	MHP1	MHP0	17
18	MHP2	MHP3	MHP0	MHP1	18
19	MHP3	MHP0	MHP2	MHP1	19
20	MHP3	MHP0	MHP1	MHP2	20
21	MHP3	MHP1	MHP0	MHP2	21
22	MHP3	MHP1	MHP2	MHP0	22
23	MHP3	MHP2	MHP0	MHP1	23
24	MHP3	MHP2	MHP1	MHP0	24

scheme, the serial-parallel data transmission technique is used to represent the data bit by a set of distinct MHP pulses. A simple switch matrix architecture is proposed to create the pulse sequence by switching the incoming 4-MHP pulses shown in Fig. 2. Each unique of the pulse sequence is assigned for a distinct mobile agent to encode the data. The proposed data encoding scheme is supported a total of n! data channels by applying the permutation technique using n-number of unique MHP pulses. Hence, a unique sequence of pulse pattern is developed by encoding the MHP orthogonal pulses to transmit binary data for each channel.

In Table II shows that the sequence of data pattern is generated by the permutation of 4-distinct orthogonal pulses. The MHP pulse set has the orthogonality property that coexists at a certain time slot with sharing the same bandwidth of each data channel. All the 24 pulse sequences are then superimposed with their corresponding time slots to create a unified pulse sequence (UPS) before to transmit through the transmitting antenna. The UPS occupies 4-time slots compare to a single time slot in conventional IR-UWB system. However, in the proposed scheme the UPS spreading 4 different time slots that supports 24 data bits compared to 4 data bit in the conventional IR-UWB system. The net data rate improvement with the proposed scheme becomes 24/4 = 6 times than the conventional system [11]. This data compression scheme takes place without using any sophisticated digital signal processing. The benefit of the proposed scheme is the simultaneous pulse spectrum sharing with supporting high-density data compression. In the data recovery section, the UPS will receive and apply the cyclic pulse elimination technique to decode the individual pulses from composite signal. Then the eliminated pulses will match with the prior known pulse sequences template. The decoded pulse sequence will indicate the presence or absence of data.

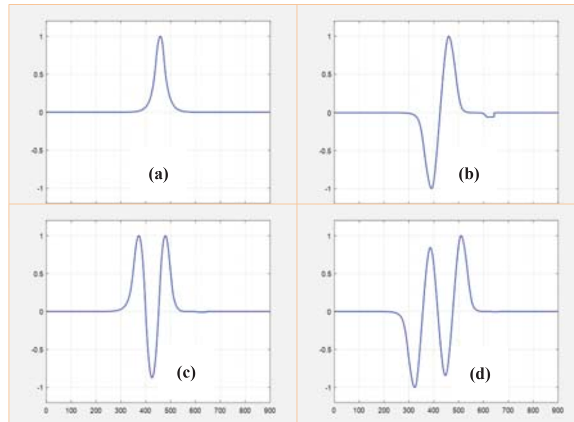


Fig. 4. Modified Hermite pulses in time domain (a) MHP0, (b) MHP1, (c) MHP2, and (d) MHP3.

IV. SIMULATION RESULTS AND DISCUSSION

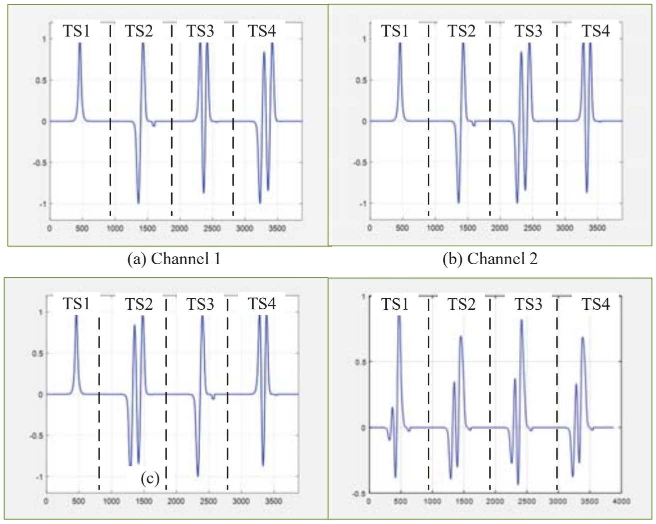
The proposed encoding scheme is done using the MHP pulse set by MATLAB coding while the different orders MHP pulses are generated by MATLAB Simulink model. Fig. 4 represents the 4-different MHP pulses in time domain. All the MHP pulses are normalized within the amplitude ranges from -1 to 1. The orthogonality of Hermite pulses offer to superimpose all the pulses and make a composite signal to increase the data transmission rate by supporting multi-user communication within the same frequency band. The simulation results of pulse sequences generation are shown in Fig. 5. In Fig. 5 (a), (b), and (c) indicates the distinct data channel, where data comes from channel 01, 02 and 24 respectively. Due to the orthogonality of the MHPs at a certain time slot, the entire pulse sequence can use the same bandwidth and add them to make a composite signal. In Fig. 5 (d) represents the composite signal of all 24-pulse sequences.

TABLE III

COMPARISON OF THE PROPOSED SCHEME WITH THE STATE- OF-THE-ART

	[12]–[14]	[12], [13], [15]	[10], [12], [16]	[11]	Proposed
Method	FHSS	DSSS	OFDM	Pulse	Pulse sequence
Technology	Bluetooth	IEEE 802.11b,Zigbee	IEEE 802.11a	IR-UWB	IR-UWB
Modulation	G/BPSK	O-QPSK, BPSK	256 QAM	PPM	PPAM
Data rate	1 Mbps	2 Mbps, 250 kbps	54Mbps	150 Mbps	6-times of [11]
Bandwidth	1 MHz	2 MHz	160 MHz	(3.1-10.6)GHz	(3.1-10.6)GHz
Power (mW)	10	36.9	lower	lower	lower

The comparison of proposed scheme with the state-of-the-art is shown in Table III. The spreading code is required in digital signal transmission technique to spread the bandwith of message signal. One the other hand, no need extra frequency translation in analog IR-UWB system due to its larger bandwidth. The analog IR-UWB system mapped the digital data bit without any sophisticated DSP algorithm. In addition, the proposed data encoding scheme will also enhance the data secure communication by randomly generated the pulse sequences.



(a) Channel 1 (b) Channel 2

(c) Channel 24 (d) Composite signal

Fig. 5. Pulse sequence represents the (a) channel 01, (b) channel 02, (c) channel 24, and (d) composite signal.

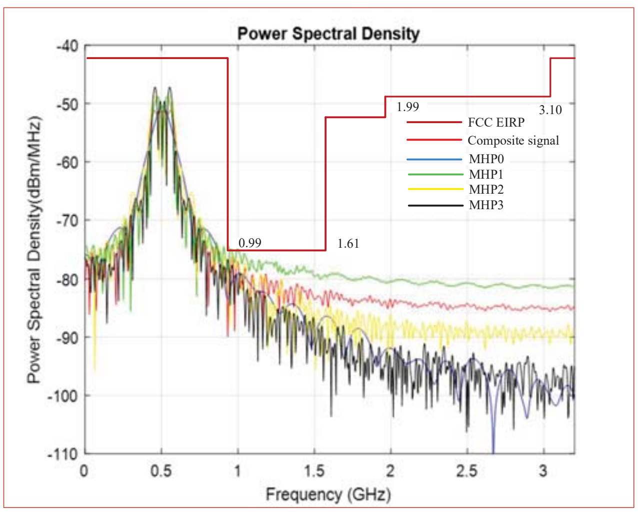


Fig. 6. The power spectral density of the composite signal, MHP0, MPH1, MHP2, and MHP3 after 500 MHz frequency shifting.

The power spectral density of the composite signal and the different MHP pulses are plotted in Fig. 6. The power spectral density of all MHP pulses and their composite signal meets the FCC Equivalent Isotropically Radiated Power mask for indoor communications. This power spectral density curve indicates that these MHP set could be used in UWB communication.

V. Conclusion

A novel energy-efficient data encoding scheme is presented in this paper. The pulse sequence is generated using a modified Hermite pulse set for multi-user applications. The simulation results indicate that the proposed data encoding scheme can achieve up to 24-distinct data channels for 4 distinct orthogonal pulses to transmit data simultaneously without requiring additional spectral bandwidth. The proposed data encoding scheme also increases data volume by 6-times for 4-distinct orthogonal MHP pulse system by sharing the same spectral bandwidth. In compare to data rate improvement with [9], [10] the proposed scheme improves (n-1)! times for the n-Hermite pulse system. The orthogonal Hermite pulse-based data encoding architecture indicates that the proposed data transmitter makes the model less complex and efficient for spectrum-efficient multichannel communication.

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