

Improving the Throughput of Sensor Network Wake-Up Radios using Block Orthogonal Codes

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Abstract—We propose the use of a block orthogonal code to reduce the symbol error rate, and therefore improve the throughput, of wake-up radios used in sensor networks. Currently proposed wake-up radios that use, for example, on-off keying modulation focus on integrated circuit design for low power operation. However, they do not take error correction coding into account and therefore increase the error rates and reduce the node lifetime. We develop a system model to evaluate the throughput of our proposed scheme. We implement a simulation of this model and show that our approach significantly improves the throughput of these radios. When compared with on-off keying modulation using 8b10b encoding we can achieve up to a factor of 10 improvement in the radio’s throughput without any additional hardware or energy consumption.

Keywords—wake-up radio; error-correcting code (ECC); wireless sensor network

I. INTRODUCTION

Energy efficiency is an important challenge for resource-constrained sensor networks [1], [2]. MAC protocols with low power listening can reduce the energy consumption, but idle listening still exists. Wake-up radios can eliminate the idle listening of nodes efficiently. Most wake-up radios use On-Off Keying (OOK) modulation to reduce the hardware complexity in order to provide low power circuits [3], [4]. Low power wake-up radios with high Symbol Error Rates (SERs) will have many false alarms, waking up their respective higher power data radios and increasing retransmissions. This means they will effectively reduce the throughput of wake-up radios. Many studies have explored solutions to improve the SER of wake-up radios through different modulation techniques [5], [6], such as Pulse Wave Modulation (PWM) and Pulse Position Modulation (PPM), or through address coding schemes [3], [4].

In [5], [6] PWM and PPM are proposed in order to achieve a lower SER for wake-up radio. However, they provide a limited improvement on the SER for wake-up radios and don’t consider Error Correction Codes (ECC) in order to improve the throughput.

The address coding schemes in [3], [4] provide a longer wake-up sequence in order to reduce false alarms. However, they don’t improve the SER through modulation, efficient encoding, or ECC. The longer wake-up sequence also increases the energy consumption of the radio.

In this paper we propose to use *block orthogonal codes* to improve the SER and throughput of wake-up radios without the use of additional energy.

The remainder of this paper is organized as follows. In section II we describe our proposed block orthogonal algorithm. We then carry out a theoretical analysis of our system in section III. In section IV we do a performance evaluation and finally in section V we conclude the results of our work.

II. BLOCK ORTHOGONAL ALGORITHM

Our proposed block orthogonal code algorithm is shown in Fig. 1. The algorithm improves the SER and throughput using coherent OOK modulation with a matched filter through an Additive White Gaussian Noise (AWGN) channel. The sender generates the information bits, groups the bits into pairs, and then maps each pair into its corresponding symbol. Then, it sends the symbols using the block orthogonal code and OOK modulation, to the wake-up radio. The wake-up radio receives the signal and uses OOK demodulation to retrieve the bitstream. The AWGN noise is suppressed by using an oversampling factor of N_{os} . The correlation values are then determined using the

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1:      /* generate data source */
2:      for i←1 to N do
3:          Generate quaternary data sources Ds
4:      end for
5:      /* block orthogonal coding */
6:      Convert Ds to block orthogonal codes
7:      /* add noise, demodulation,
oversampling and correlation*/
8:      for i←1 to N do
9:          Add AWGN noise
10:         Do OOK demodulation
11:         Do oversampling receiving signals
12:         foreach samples
13:             Calculate correlation values C
14:         end for
15:         /* reduce noise*/
16:         for i←1 to Length (C) do
17:             Run low pass filter for C
18:         end for
19:         /* decision */
20:         Find local maximum correlation values Cmax
21:         Determine detected data Dd by Cmax
22:         /* performance evaluation*/
23:         Compare Ds with Dd
24:         Calculate BER, SER and throughput

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Figure 1. Block orthogonal code algorithm

oversampled values and a copy of the ideal block orthogonal code symbols. The wake-up radio uses a low pass filter (LPF) on these correlation values to further suppress any remaining AWGN noise, reducing undesired peak values. The local maximum of the filtered signal is then output as the valid correlation value. Based on these valid correlation values, the wake-up radio determines the detected symbols.

In order to test the above system, we calculate the Bit Error Rate (BER), the SER, and the throughput with varying Signal-to-Noise Ratios (SNRs) by comparing the source data with the received data.

III. THEORETICAL ANALYSIS

A. System Model

The block orthogonal code uses N_{cps} chips per symbol and an oversampling factor of N_{os} to suppress noise. The N_{os} reduces the noise variance (noise power) by a factor of $1/N_{os}$. The block orthogonal code can be represented as the M -ary block orthogonal code $O(N_{cps}, k)$ with diversity $L = N_{cps}/M$, where $M = 2^k = 4$, $k = 2$ and N_{cps} chips. The average SNR per chip, SNR_c , is given by

$$SNR_c = \frac{k}{L} SNR_b N_{os} = \frac{k M N_{os} SNR_b}{N_{cps}} = \frac{8 N_{os} SNR_b}{N_{cps}}, \quad (1)$$

where SNR_b is the SNR per bit. The symbol (code word) error probability, p_{es_orth} for M -ary block orthogonal signaling with diversity L and the minimum hamming distance d_{min} is given by

$$p_{es_orth} = 1 - \sum_{i=0}^{N_{cc}} \binom{N_{cps}}{i} p_{ec_ook}^i (1 - p_{ec_ook})^{(N_{cps}-i)}, \quad (2)$$

where the minimum hamming distance d_{min} is given by

$$d_{min} = 2L = 2 \frac{N_{cps}}{M} = \frac{N_{cps}}{2}, \quad (3)$$

the number of chips, N_{cc} , which can be corrected by M -ary block orthogonal signaling with diversity L and the minimum hamming distance d_{min} is given by

$$N_{cc} = \lfloor \frac{d_{min} - 1}{2} \rfloor = \lfloor \frac{N_{cps}}{M} - \frac{1}{2} \rfloor = \lfloor \frac{N_{cps}}{4} - \frac{1}{2} \rfloor, \quad (4)$$

the chip error probability of coherent OOK modulation, p_{ec_ook} , through a matched filter is given by [7]

$$p_{ec_ook} = Q(\sqrt{SNR_c}). \quad (5)$$

The value of SNR_c is given by

$$\frac{8 N_{os} SNR B_s}{N_{cps} R}, \quad (6)$$

where B_s is the noise bandwidth, R is the wake-up radio's data rate, and SNR is the Signal-to-Noise Ratio (SNR).

B. Symbol and Packet Error Rate Analysis

To explore the performance of the varying modulation and encoding schemes, we analyze their SER and Packet Error Rate (PER). From (2), the packet error probability, p_{ep_orth} for a block orthogonal code is given by

$$p_{ep_orth} = (1 - p_{es_orth})^{L_{wupr}/k} = (1 - p_{es_orth})^{0.5 L_{wupr}}, \quad (7)$$

where the wake-up packet length is L_{wupr} bits. For PWM modulation, we use the BER in [6]. In terms of other encoding schemes, we apply the system model in [8] to analyze their SER and PER. The relation between symbol error and bit error probability of binary coherent OOK modulation, p_{es_ook} , through a matched filter is given by

$$p_{es_ook} = p_{eb_ook} = Q(\sqrt{SNR_b}) = Q\left(\sqrt{\frac{SNR B_s}{R}}\right). \quad (8)$$

The packet error probability of OOK modulation with 8b10b coding, p_{ep_8b10b} is given by

$$p_{ep_8b10b} = 1 - (1 - p_{es_ook})^{1.25 L_{wupr}}. \quad (9)$$

The packet error probability of OOK modulation with hamming code (7, 4), p_{ep_h74} , that can detect and correct one error, is given by

$$p_{ep_h74} = 1 - ((1 - p_{es_ook})^7 + 7p_{es_ook}(1 - p_{es_ook})^6)^{0.25L_{wurp}}. \quad (10)$$

C. Throughput Analysis

For a performance comparison of the block orthogonal code with other modulation schemes and encodings, we will now analyze the respective throughputs. We assume the system bandwidth is the same as the noise bandwidth B_s , the wake-up packet length is L_{wurp} bits, the transmitter sends L_{packet} wake-up packets, and the Packet Reception Rate (PRR) of the wake-up radio is given by

$$PRR_{wur} = 1 - p_{ep}, \quad (11)$$

where PRR_{wur} is the wake-up radio's PRR, and p_{ep} is the wake-up radio's packet error probability with varying modulation types and encodings. The throughput S_{wur} is given by [9], [10]

$$S_{wur} = \frac{PRR_{wur}B_s}{L_{packet}L_{wurp}}. \quad (12)$$

IV. PERFORMANCE EVALUATION

We first conduct a simulation to validate our system model. Then, in order to explore the performance of our approach, we build the system model into a Matlab simulator to expose the salient characteristics, such as SER and throughput. The system model uses our algorithm as shown in Fig. 1. Furthermore, for exploring the performance comparison of our approach with other modulation and encoding schemes, we show the characteristics of other modulation and encoding schemes.

The block orthogonal code $O(8, 2)$ with diversity $L = 2$, $n = 8$, $k = 2$, and $M = 4$ is defined as

$$\begin{aligned} \text{Let } c_i \in \{0, 1\}, i \in \{1, 2, \dots, 8\}, \text{ thus} \\ s_1 = \{c_i\} = \{11000000\} \\ s_2 = \{c_i\} = \{00110000\} \\ s_3 = \{c_i\} = \{00001100\} \\ s_4 = \{c_i\} = \{00000011\} \end{aligned} \quad (13)$$

where the chip c_i is the i_{th} chip per symbol, and the symbols s_1, s_2, s_3, s_4 represent the bit pairs 00, 01, 10, and 11, respectively. The simulation block diagram is shown in Fig. 2.

The wake-up signal is designed as a packet that encodes a wake-up identification (ID) value of 16 bits and an additional

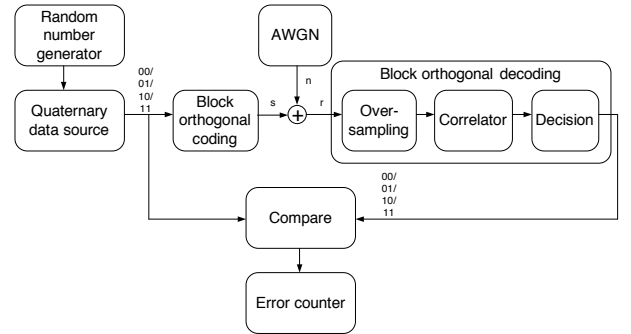


Figure 2. Simulation block diagram

out-of-band data of 24 bits, for a total of 40 bits. The wake-up ID length has an addressing capability for 65,536 nodes. The out-of-band data length depends on the desired information. If the wake-up ID matches the node ID, the wake-up radio will send an interrupt signal to wake up the receiving node's MCU. Then, the sender will send a message to the wake-up radio. If the wake-up ID does not match the node ID, the wake-up radio will ignore the wake-up signal. Then, the wake-up radio will wait one message time for the next wake-up signal. Thus, the latencies are the same when either false or successful wake-up signals occur.

For high sensitivity wake-up radio design [11], we use the Micrf221 [12] 916.5 MHz OOK receiver. It achieves a sensitivity of -109 dBm at 1 kbit/s with a BER of 10^{-2} . It performs $15 \mu A$ with the low power listening duty cycle of 0.15%. It uses coherent OOK modulation as it has a built-in phase lock loop synthesizer. It has a data rate $R = 5.264$ kbit/s and a demodulation bandwidth of $B_s = 6.85$ kHz. We assume the demodulation bandwidth B_{dem} is the same as the noise bandwidth B_s for the theoretical analysis and simulation. In terms of the sender sending the wake-up signals, we use the IEEE 802.15.4 compliant data radio AT86RF212 [13] as a 916.5 MHz OOK transmitter. It has a data rate of $R_d = 20$ kbit/s and a continuous wave (CW) mode at a carrier frequency of 916.3 MHz + 0.1 MHz. It generates the OOK modulated wake-up signals using an antenna switch. The OOK modulated wake-up signals comprise the block orthogonal symbols (code word) as (13).

Table IV-B summarizes the theoretical analysis and simulation parameters for the system model of the high sensitivity wake-up radio using the Micrf221 chip. We assume the preamble time $T_{preamble}$ is consecutive wake-up packet times T_{wurp} , as wake-up radio, using duty cycled low power listening operation, requires at least one wake-up packet to receive the wake-up address of 16 bits and information of 24 bits at data rate of 5.264 kbit/s. In terms of the message time T_{msg} , we use a frame length of 127 bytes to be the message using the data rate of 20 kbit/s.

A. Symbol Error Rate

As the simulation uses 10^5 symbols, that allows us to estimate the simulated SER of 10^4 reliably. The curve of the simulated symbol's SER is based on reliable simulated results that have at least 10 errors. The analytical curve shows the upper bound SER and is the ceiling of the simulated curve. We compare SER with OOK and PWM modulation.

From Fig. 3(a), we can observe that in order to achieve a SER of 10^{-3} , OOK modulation requires an SNR of 9 dB, PWM modulation requires an SNR of 10 dB, while the block orthogonal code achieves an SER of 10^{-3} at an SNR of 1 dB. Given an SER of 10^{-2} , the block orthogonal code's SNR is -1 dB which is better than OOK's SNR of 6 dB and PWM's SNR of 7 dB. Therefore, our block orthogonal code algorithm has a better SER, at a given SNR, than OOK and PWM modulation as our algorithm provides error-resilient capability to suppress the out-of-band and the in-band interference when the receive signal strength is below the noise. We observe that the block orthogonal code provides up to 8 dB of coding gain at an SER of 10^{-3} and is applicable to the wake-up radios with orthogonal signaling.

B. Throughput

To explore the throughput of the block orthogonal code with other modulation and encoding schemes, we use the throughput model of (12) to determine the performance of the wake-up radio.

In Fig. 3(b), the throughput of the block orthogonal code has the best performance in modulation and encoding schemes at a given SNR. The block orthogonal code requires lower SNR in order to achieve the full throughput as it has error-resilient capability. Other modulation and encoding schemes need higher SNR to overcome the noise interference in order to reach the full throughput.

We observe that the throughput curves provide three regions: sleep region, transitional region, and wake-up region. The sleep region is bounded by 10% of throughput. The transitional region is bounded between 10% and 90% of throughput. The wake-up region is bounded by 90% of throughput. The block orthogonal code has smallest transitional region, largest wake-up region and smallest SNR of the wake-up point, which is defined as the left edge of the wake-up region. It has no additional energy as the energy of a symbol is the same as the energy of a pair of bits. It has a cost of bandwidth expansion factor $n/k = 16/2 = 8$. The OOK modulation with 8b10b encoding scheme has higher SNR wake-up point than OOK modulation as it has a code rate of $1/1.25$ and requires more bit energy to provide error detection capability. It has a cost of bandwidth expansion factor of 1.25 and extra energy. The OOK modulation with Hamming code (7,4) has the larger wake-up region, with a code rate $4/7$, than OOK modulation as it has one error correction capability and a cost of bandwidth expansion

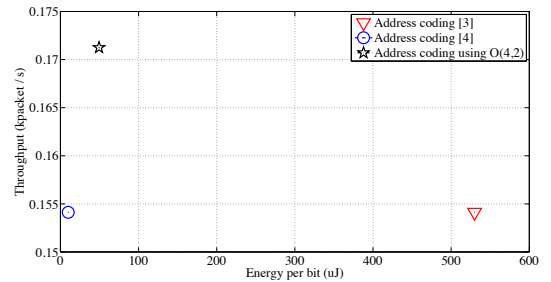


Figure 4. Throughput versus energy per bit

factor $7/4$ and extra bit energy. The PWM with bandwidth expansion factor $k = 4$ in [6] has smaller wake-up region than OOK modulation as its SER is a little worse than OOK modulation with data rate of $R = 5.264$ kbit/s and a demodulation bandwidth of $B_s = 6.85$ kHz. However, the wake-up regions of other modulation and encoding schemes are not as large as the wake-up region of the block orthogonal code.

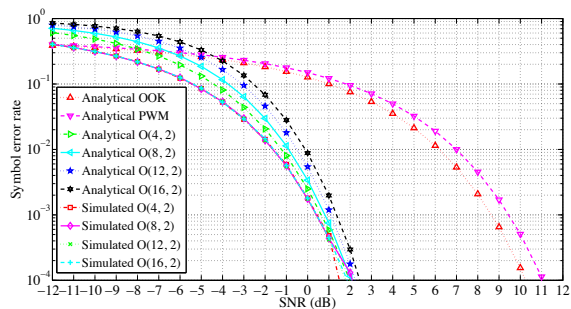
In terms of energy consumption of the block orthogonal code, the energy of a symbol is the same as the energy of a pair of bits. The energy of a chip is the energy of a symbol divided by L . This means that the block orthogonal code doesn't require any additional energy to provide better SER. The comparison of energy consumption of the block orthogonal code with other address coding schemes [3], [4] is shown in Fig. 4. We normalize the transmission power to one in order to evaluate energy consumption and throughput. As [3] has a larger bit time period, it has a larger energy consumption. The work in [4] uses a higher data rate, so it has a smaller bit time period and energy consumption. However, they don't provide high throughput. The block orthogonal code $O(4,2)$ achieves the highest throughput with proper energy consumption.

V. CONCLUSION

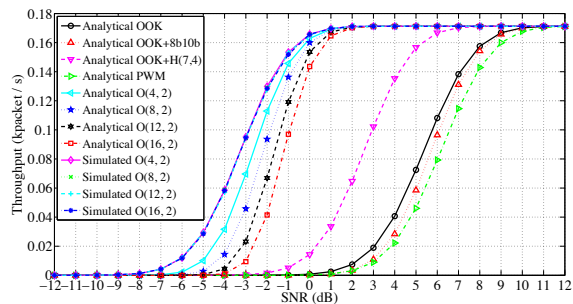
This paper proposes a block orthogonal code to improve the SER and throughput of wake-up radios for sensor networks. The simulation results demonstrate that our block orthogonal code enhances the SER and throughput of the wake-up radio significantly. The proposed approach benefits wake-up radios in order to improve their reliability and availability for sensor networks.

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(a) Symbol error rate



(b) Throughput

Figure 3. Experimental results as a function of SNR

Table I
ANALYSIS AND SIMULATION PARAMETERS

Wakeup Radio			
Description	Parameter	Value	Units
Number of transmission symbol	N	10^5	symbols
Number of chips per symbol	N_{cps}	4, 8, 12, 16	chips/symbol
Oversampling rate	N_{os}	4	samples/chip
Diversity	L	1, 2, 3, 4	chips
Noise bandwidth	B_s	6850	Hz
Data rate	R	5264	bits/s
Number of wake-up packet	L_{packet}	1	packet
Wake-up packet length	L_{wurp}	40	bits
Wake-up address length	L_{wurp_addr}	16	bits
Wake-up information length	L_{wurp_inf}	24	bits

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