# CYCLIC ORTHOGONAL CODES IN CDMA-BASED ASYNCHRONOUS WIRELESS BODY AREA NETWORKS

Ali Tawfiq<sup>†</sup> Jamshid Abouei<sup>\*</sup> Konstantinos N. Plataniotis<sup>†</sup>

 <sup>†</sup> The Edward S. Rogers Sr. Dept. of Electrical and Computer Engineering, University of Toronto, Toronto, Canada Email: {atawfiq, kostas}@comm.utoronto.ca
\* Dept. of Electrical and Computer Engineering, Yazd University, Yazd, Iran, Email: abouei@vazduni.ac.ir

#### ABSTRACT

This work considers a CDMA-based Wireless Body Area Network (WBAN) where multiple biosensors communicate simultaneously to a central node in an asynchronous fashion. The main goal of this paper is to present an augmentation protocol for the physical layer of the IEEE 802.15.6 specifications with focus on the Multiple Access Interference (MAI) mitigation in a proactive WBAN. The proposed methodology uses a new set of orthogonal codes from the conventional Walsh-Hadamard matrix which has the special property of "cyclic orthogonality". This property ensures that the asynchronous nature of the WBAN does not produce MAI amongst the multiple on-body sensors. The work investigates the optimality of such codes in WBANs from the link Bit Error Rate (BER) performance. We show that the proposed spreading codes outperform conventional non-cyclic orthogonal spreading codes in a practical Rayleigh fading environment.

*Index Terms*— Wireless Body Area Network (WBAN), CDMA, Multiple Access Interference (MAI), Cyclic Orthogonal Walsh-Hadamard Codes (COWHC).

### 1. INTRODUCTION

Wireless Body Area Networks (WBANs) support a broad range of medical/non-medical applications in health care, medicine, sports, etc. Of interest is the use of WBANs for the continuous monitoring of physiological signals for both diagnosis and prevention [1]. Those include on-body measurements such as Electrocardiogram (ECG), Electroencephalogram (EEG), temperature and blood pressure, and/or accurate diagnosis of vital signs of the patients' in-body by tiny implantable sensors. Due to the medical regulations, the protocols for WBANs must comply with the maximum transmit power, frequency of operation and the minimum interference posed on other medical devices. On the other hand, the protocols in such WBANs where multiple biosensors communicate to a central node must support high rate of reliability, immunity to noise and multiple access capabilities. In such networks having sensors with their predetermined active mode durations and data rates introduces time and data rate asynchronicity. When multiple sensors access a common transmission channel with such asynchronicity existent they will experience packet collision. Of interest is the use of multiple access techniques to combat the problem of packet collision in WBANs. There are a number of works in the literature that address this problem using traditional Time Division Multiple Access (TDMA) scheduled protocols and time hopping sequences [2, 3], asynchronous random wake up/sleeping algorithms [4], and Direct Sequence Code Division Multiple Access (DS-CDMA) with orthogonal spreading codes. The DS-CDMA physical layer scheme is the most promising for use in WBANs since it meets the following requirements: i) collision-free, ii) multipath resilient properties, iii) supports various data rates, iv) uses available frequency and time resources efficiently [5].

One challenge faced in CDMA-based WBANs is to utilize the proper spreading codes with minimum mutual crosscorrelation to mitigate Multiple Access Interference (MAI) which leads to the transmit energy saving as well. However, the problem in using spreading codes is the loss of orthogonality due to the MAC/PHY layers asynchronicity (in particular in asynchronous wake up process for the nodes), and/or multipath signal propagation. In this paper, to address this problem in this emerging application we revisit the work in [6] and present a DS-CDMA based asynchronous WBAN that utilizes a unique set of Cyclic Orthogonal Walsh-Hadamard Codes (COWHC) to eliminate MAI caused by packet collision. Our contribution is to spread each sensor node with a unique code from the COWHC set, which will ensure during the de-spreading at the central node we have eliminated the effect of MAI. The work studies the optimality of using such codes in DS-CDMA WBANs compared to commonly used non-cyclic orthogonal Walsh-Hadamard codes from the link Bit Error Rate (BER) performance point of view.

The rest of the paper is organized as follows: In Section 2,

the WBAN system model is introduced and Section 3 details the COWHC. Section 4 demonstrates the simulation results and finally the conclusion is presented in Section 5.

#### 2. WBAN SYSTEM MODEL

In this work, we consider a CDMA-based body-centric wireless sensor network consisting of K on-body biosensors denoted by  $S_1, S_2, ..., S_K$ , and a Central Control Unit (CCU). It is assumed that each  $S_i$ , i = 1, ..., K, transmits its packets in a single-hop to the CCU. To keep the complexity of the transceiver hardware as low as possible, we assume that all the biosensors transmit data over the same frequency band. We assume proactive communications between  $S_i$ 's and the CCU, meaning that each  $S_i$  transmits periodically an equal amount of data per time unit to the CCU which is statistically independent of data transmitted from the  $S_i$ ,  $i \neq j$ . Unlike the CCU which has a power source, the biosensors have power-constrained batteries, and they need to reduce their power consumptions to prolong the lifetime of the network. For this purpose, we introduce a duty-cycling mechanism illustrated in Fig. 1 which achieves significant energy saving in both circuits and signal transmission.



Fig. 1. Practical duty-cycling process in a proactive WBAN.

Without loss of generality and for ease of our analysis, we assume that the bit duration of  $m_{\ell} \in \{-1, +1\}$ , denoted by  $T_b$ , is the same for all  $S_i$  nodes and that biosensors are unaware of the other nodes' wake up process. For the proposed CDMA-based WBAN, the bit stream is directly multiplied by COWHC with chip duration  $T_c$  and the processing gain  $N \triangleq \frac{T_b}{T_c}$ . It is assumed that N is fixed for all  $S_i$ nodes. The length of Walsh-Hadamard codes is a function of different parameters such as the number of on-body biosensors, the available spectrum, and the targeted performance of the network. The necessary condition to avoid MAI in the proposed scheme is to choose the length of  $N = 2^k$  such that  $K \leq k + 1$ , as shown in Section 3.

Denoting  $s_i$  as the transmitted signal from sensor *i*, the received signal at the CCU is given by

$$\mathcal{X}_r = \sum_{i=1}^K w_i s_i + \eta, \tag{1}$$

where  $w_i$ 's, i = 1, ..., K are unique cyclic orthogonal codes, and  $\eta$  is an Additive White Gaussian Noise (AWGN). At the CCU in order to decode for  $s_i$ , the model simply de-spreads  $\mathcal{X}_r$  with code  $w_i$  as follows:

$$\hat{s}_{i} = w_{i} \mathcal{X}_{r} = w_{i}^{2} s_{i} + \sum_{\substack{j=1\\j\neq i}}^{K} w_{i} w_{j} s_{j} + w_{i} \eta, \qquad (2)$$

where by definition  $w_i^2$  will equal to 1, and  $w_i w_j$  will evaluate to zero cross-correlation (due to orthogonality). Hence we end up with a decoded signal  $\hat{s}_i = s_i + w_i \eta$ .

Moreover, it is shown in [7] that the root mean square (rms) delay spread for indoor applications is in the order of nanoseconds, which is small compared to the symbol duration  $T_s = 1.66\mu s$  to  $T_s = 5.33\mu s$  obtained from the Narrowband PHY Specifications of the IEEE 802.15.6 standard draft [8] and [9]. Hence it is reasonable to assume a flatfading channel model for the proposed WBAN. Furthermore, the indoor environment at which our proposed WBAN operates in involves many obstacles (i.e. wall, furniture, etc), which leads to reduced Line-Of-Sight (LOS). This behavior suggests a Rayleigh fading channel model.

### 3. CYCLIC ORTHOGONAL WALSH-HADAMARD CODES (COWHC)

Walsh-Hadamard codes have been widely used in DS-CDMA communications. Inherently the codes generated from the Walsh-Hadamard Matrix  $\mathbf{H}_{2^k}$  are orthogonal in the zerophase. The Walsh-Hadamard matrix is a special matrix of size  $N \times N$  where  $N = 2^k$  is a power of 2. Setting  $\mathbf{H}_1 = [1]$ , a higher dimensional Hadamard matrix  $\mathbf{H}_{2^k}, k > 1$  is produced as follows:

$$\mathbf{H}_{2^{k}} = \begin{bmatrix} \mathbf{H}_{2^{k-1}} & \mathbf{H}_{2^{k-1}} \\ \mathbf{H}_{2^{k-1}} & -\mathbf{H}_{2^{k-1}} \end{bmatrix} = \mathbf{H}_{2} \otimes \mathbf{H}_{2^{k-1}}, \quad (3)$$

where  $\otimes$  denotes the Kronecker product. The rows in each of the Hadamard matrices generated above are mutually orthogonal to each other. The orthogonality property of the Walsh-Hadamard codes is lost if the codes are phase shifted. Shifted codes when cross-correlated result in a non-zero cross-correlation value. If these non-orthogonal codes are used in an asynchronous WBAN, we will experience MAI as it was explained before. To combat this problem, we use a special set of Hadamard codes extracted from the  $\mathbf{H}_{2^k}$  that are orthogonal to each other at every phase shift  $\phi$ , where  $\phi = 0, 1, \dots, 2^k - 1$  [6]. Lets denote  $\mathbf{W}(2^k, k)$  as the set of  $2^k$  codes generated from the  $\mathbf{H}_{2^k}$  matrix,  $k \ge 1$ . In this case, the cross-correlation for codes  $w_1, w_2 \in \mathbf{W}(2^k, k)$  at phase-shift  $\phi$  is defined as follows:

$$R_{w_1w_2}(\phi) = \sum_{i=1}^{2^k} w_1(i)w_2(i+\phi), \qquad (4)$$

where ideally we would want  $R_{w_1w_2}(\phi)$  in (4) to be zero for all possible  $\phi = 0, 1, ..., 2^k - 1$ .



**Fig. 2.** Cross-correlation of W(8,3) codes at the (a) zerophase, (b) first phase, and (c) second phase

It is observed from Fig. 2 that the cross-correlation between the codes of W(8,3) at the zero-phase are all zero as expected. However, in the first and second phases we see that only "some" codes exhibit zero cross-correlation. We are particularly interested in these sets of codes. When examined, we can find a unique set of K = k + 1 = 4codes from the W(8,3) that have zero cross-correlation in all phases  $\phi = 0, 1, 2, \cdots, 7$ . Lets denote  $w_i, i \in 1, \cdots, 8$ as the code extracted from the  $i^{th}$  row of W(8,3). By inspection, we can see that a possible COWHC set is generated from  $w_1 = (1, 1, 1, 1, 1, 1, 1, 1), w_2 = (1, -1, 1, -1, 1, -1, 1, -1), w_4 = (1, -1, -1, 1, -1), w_4 = (1, -1, -1, -1, -1), w_4 = (1, -1,$ 1, -1, 1, 1, -1, -1, 1), and  $w_5 = (1, 1, 1, 1, -1, -1, -1)$ . Hence, such COWHC set can be used for spreading the sensors in the proposed WBAN and while this limits the number of active sensors to K = k + 1, it ensures that all K connections are reliable and collision free.

### 4. VALIDATION AND RESULTS

### 4.1. Simulation Setup

Matlab was used to simulate a CDMA-based WBAN that utilizes a set of COWHC. The implemented simulation model named 'Cyclic Orthogonal DS-CDMA WBAN System' is shown in Fig. 3. The system simulates a complete communication system where random data  $s_i$ , i = 1, ..., K of  $m_{\ell} \in \{-1, +1\}$  is generated in the Data Generation block. Next in the Spread and Transmit block  $s_i$  is directly multiplied by a unique spreading code  $w_i, i = 1, ..., K$ . The model uses  $w_i \in COWHC$  to simulate a cyclic orthogonal CDMAbased system, otherwise  $w_i \in \mathbf{H}_{2^k}$  for non-cyclic CDMA. In the Channel block the model sums the spread  $s_i$  of the K sensors and adds white Gaussian noise (with or without Rayleigh flat-fading). Finally, the *CCU* block involves de-spreading and decision making by using the unique spreading code  $w_i$  for sensor  $S_i$ .



Fig. 3. Cyclic orthogonal DS-CDMA WBAN system model.

The system is iteratively simulated over hundreds of duty cycles where an asynchronous network is modeled by randomly spacing out the time at which sensor  $S_i$  is 'ON' and transmitting (Fig. 4). By modeling asynchronicity as such, the system is capable of testing the robustness of COWHC when utilized in asynchronous CDMA-based WBANs.



Fig. 4. Visualization of asynchronicity in a WBAN.

The following are some critical simulation parameters used in the model: *DataLen*- the length (in bits) of data transmitted in each duty cycle, *ittTimes*- the number of duty cycles, *Fading*- logical for whether or not to simulate a Rayleigh flatfading channel, *Cyclic*- logical for whether to use COWHC or non-COWHC, and *N*- is the spreading factor (number of chips per symbol).

#### 4.2. Simulation Results

Presented in Fig. 5 is the Bit Error Rate (BER) versus Signalto-Noise Ratio (SNR) performance for two systems, one that utilizes COWHC for spreading and another with non-cyclic Walsh-Hadamard spreading codes. In this simulation, the system assumes a non-fading AWGN channel and that perfect PN code synchronization is achieved at the CCU. It is evident as shown in Fig. 5 that when using COWHC there exists a magnificent performance gain as SNR increases. This performance gain is achieved due to the cyclic orthogonality property of the COWHC as MAI is mitigated and less bits are decoded in error at the CCU. The results also hold for different spreading factors as showing in Fig. 5.



**Fig. 5**. BER versus SNR performance between COWHC CDMA and non-COWHC CDMA in non-fading environments.

The robustness of the COWHC is tested in a Rayleigh flatfading environment that imitates a practical working channel for sensors operating in the vicinity of the human body. Presented in Fig. 6 is the bit error performance for a system with COWHC for spreading compared to that with non-cyclic Walsh-Hadamard codes. It is noticeable that COWHC also outperforms in a flat-fading environment. Hence the cyclicorthogonality property is preserved in a Rayleigh flat-fading channel and the effect of MAI is eliminated which yields to less bits decoded in error at the CCU.

## 5. CONCLUSION

Presented is a novel approach to be used as an augmentation protocol for the IEEE 802.15.6 specifications in asynchronous CDMA-based WBANs where a special set of cyclically orthogonal Walsh-Hadamard spreading codes are used to eliminate multiple access interference. With mutual crosscorrelation of zero at every time shift, these sets of codes are able to accommodate for the asynchronicity caused at the MAC/PHY layers and/or by multipath signal propagation. By uniquely spreading the sensor data with COWHC at each sensor node and consequently de-spreading at the CCU with the same code, this will have effectively eliminated the effects of MAI. Furthermore, when compared to CDMA-based WBAN



**Fig. 6**. BER versus SNR performance for COWHC and non-COWHC in a Rayleigh flat-fading environment and N=64

with non-COWHC in a practical WBAN environment with a Rayleigh flat-fading AWGN channel, COWHC distinctly outperforms non-COWHC from the Bit-Error-Rate point of view.

#### 6. REFERENCES

- R. Schmidt, T. Norgall, J. Mrsdorf, J. Bernhard, and T. Von Der Grun, "Body area network BAN: a key infrastructure element for patient-centered medical applications," *Biomed Tech (Berl)*, vol. 47, pp. 365–368, Jan. 2002.
- [2] J. Zeng, H. Minn, and L. S. Tamil, "Time hopping directsequence CDMA for asynchronous transmitter-only sensors," in *Proc. IEEE Military Communications Conference (MIL-COM'08)*, Nov. 2008.
- [3] R.A. Tannious and A. Scaglione, "Physical layer design of distributed proportional fair scheduling in wireless body area networks," in *Proc. IEEE PIMRC'10*, Sept. 2010, pp. 78–83.
- [4] C. Hua and T.-S. P. Yum, "Asynchronous random sleeping for sensor networks," ACM Trans. on Sensor Networks, vol. 3, no. 3, Aug. 2007.
- [5] Wen-Bin Yang and K. Sayrafian-Pour, "A DS-CDMA interference cancellation technique for body area networks," in *Proc. IEEE PIMRC'10*, Sept. 2010, pp. 752–756.
- [6] J. Abouei, "A set of cyclic orthogonal codes acquired from Walsh-Hadamard matrix," in *Proc. 34th International Mathematics Conference*. Shahrood, Iran, Sept. 2003.
- [7] H. Karl and A. Willig, Protocols and Architectures for Wireless Sensor Networks, John Wiley and Sons Inc., first edition, 2005.
- [8] "Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Wireless Personal Area Networks (WPANs) used in or around a body.," *IEEE P802.15.6/D04*, pp. 182–186, June. 2011.
- [9] S. Ullah and K. S. Kwak, "Throughput and delay limits of IEEE 802.15.6," in Proc. Wireless Communications and Networking Conference (WCNC), March. 2011, pp. 174–178.