Novel Multiple Access Schemes for IEEE 802.15.4a Low-rate Ultra-wide Band Systems

Hong Zhang* ***Associate Member***, Bing Hui* ***Regular Member***, KyungHi Chang* ***Lifelong Member***

ABSTRACT

The IEEE 802.15.4a specification targets the low-rate (LR) Impulse-radio (IR) ultra-wideband (UWB) system which is now widely applied in the WPANs considering rather short distance communications with low complexity and power consumption. The physical (PHY) layer uses concatenated coding with mixed binary phase-shift keying and binary pulse-position modulation (BPSK-BPPM), and direct sequence spreading with time hopping in order that both coherent and non-coherent receiver architectures are supported. In this paper, the performances of multiple access schemes compliant with IEEE 802.15.4a specification are investigated with energy detection receiver, which allow avoiding the complex channel estimation needed by a coherent receiver. However, the performance of energy detection receiver is severely degraded by multi-user interference (MUI), which largely diminishes one of the most fascinating advantages of UWB, namely robustness to MUI as well as the possibility to allow parallel transmissions. So as to improve the performance of multiple access schemes, we propose to apply the novel TH sequences as well as to increase the number of TH positions. The simulation results show that our novel multiple access schemes significantly improve the performance against MUI.

Key Words : Ultra-wideband (UWB), Multiple access, Time-hopping, Pseudo-random code

Ⅰ. Introduction

Ultra-wideband (UWB) is generally divided into two wireless systems, high data-rate transmission system (above 100 Mbps) and low data-rate transmission system (around 1 Mbps). The IEEE 802.15.4a[1] proposal is an amendment to IEEE 802.15.4 standard which targets the low-rate impulse radio (IR) UWB with low power consumption and complexity. The physical (PHY) layer defines three independent bands, sub-gigahertz (249.6-749.6 MHz), low band (3.1-4.8 GHz), and high band (6.0-10.6 GHz), which includes several channels of 500 MHz. The IR-UWB PHY uses a concatenated coding with an outer Reed-Solomon (RS) code and an inner convolutional code. Furthermore, it prescribes binary position modulation (BPM) together with binary phase-shift keying (BPSK) modulation scheme with time hopping against multi-user interference (MUI)[2]. A standard compliant device should be capable of implementing one of the two receivers, a coherent receiver (e.g., Rake receiver), or a non-coherent receiver such as energy detection receivers.

An energy detection receiver is a better choice due to its relatively simple circuitry structure considering the cost-effective receiver design with extremely low power consumption under practical implementations, for instance, the applications in wireless sensor networks. Also, it allows avoiding the complex channel estimation needed by a coherent receiver. However, the performance of energy detection receiver is demonstrated to be severely degraded by MUI, which largely

※ This work was supported by the IT R&D program of MKE/IITA [Development of Next Generation RFID Technology for Item Level Applications], Rep. of Korea.

* Mobile Telecommunications Research Lab, The Graduate School of Information Technology & Telecommunications, Inha University (zhanghong.email@gmail.com, huibing_zxo@163.com, khchang@inha.ac.kr).

논문번호 : KICS2010-04-190, 접수일자 : 2010년 4월 30일, 최종논문접수일자 : 2010년 7월 1일

diminishes one of the most fascinating advantages of UWB, namely robustness to MUI as well as the possibility to allow parallel transmissions[3,4].

Time-hopping (TH) is considered as an access scheme for multi-user IR-UWB systems. Communications over the indoor wireless channel is a technical challenge. Due to varying channel conditions depending on positions, the signal suffers from heavy multi-path propagation. The critical issue for using TH is the ability to greatly resolve multipath and the high possibility of the technology to implement and generate UWB signals with relatively low complexity. Modulation of TH baseband signal is achieved through the time shift of sub-nanosecond pulses (referred to as monocycles). As it is known that the performance of IR-UWB with energy detection receiver under multi-user environment degrades significantly and practical implementations are limited. The motivation to research on distinct types of TH sequences is to improve the performance of data transmission, reduce the Bit Error Rate (BER) and boost the multiple-access capacity. Hence, we proposed to apply the novel TH sequences as well as increase the number of TH positions. The simulation results show that our novel multiple access schemes remarkably improved the performances against MUI[5,6].

The remaining part of this paper is organized as follows. The system model of IEEE 802.15.4a is first introduced in Section II including low-rate IR-UWB, TH for multiple access and channel model. Then in Section III, we proposed novel multiple access scheme for IEEE 802.15.4a UWB and in section IV, the simulation results is shown and evaluated. Finally, conclusions are given in Section V.

Ⅱ. System Model of IEEE 802.15.4a

2.1 Low-rate IR-UWB

In IEEE 802.15.4a, a UWB impulse radio transmits a train of low duty cycle bursts[7]. A single burst consists of N_{cpb} chips, whose amplitudes are modulated by a binary scrambling sequence. The N frames build up N bits transmitted signal and a frame is made up of N_c chips with T_c seconds. The position of the burst in the kth frame represents the kth bit information, which depends on the time hopping sequence, $N_{hop} = N_c/4N_{hop}$. Thus the transmit signal is given by

$$S^{(k)}(t) = \sum_{k=-\infty}^{\infty} b_1^{(k)} p^{(k)}(t - b_0^{(k)}\Delta - h^{(k)} N T_c), \quad (1)$$

where $b_1^{(k)} \in \{\pm 1\}$ and $b_0^{(k)} \in \{0,1\}$ are the kth (binary phase shift keying) BPSK and (binary position modulation) BPM data symbol. $p^k(t)$ is a burst with N_{cpb} chips. Δ is the BPM delay. $h^{(k)}$ is the time hopping code of integer chosen in {0, 1, …, N_{hop}-1}. Both the scrambling sequence and time hopping sequence are generated by a linear feedback shift register (LSFR) described in the 802.15.4a specification.

The parameters of N_{cpb}, N_{hop}, N_c, and T_c used in this paper are given in Table 1 compliant with 802.15.4a PHY layer specification. The mandatory data rate of 0.87 Mbit/s (we consider the case with Reed-Solomon (RS) code only) is adopted with the mean pulse-repetition frequency (MPRF) 3.90 MHz.

Table 1. Parameters of IR-UWB PHY layer

N_{cpb}	N_{hop}	N_c	T_c (ns)	Bit Rate (Mb/s)	Mean PRF (MHz)
4	32	512	2	0.87	3.90

2.2 Pseudo-random TH Spread-spectrum

In IEEE 802.15.4a PHY layer, the Pseudo-random (PR) TH code shall be generated from a common PR binary sequence scrambler, which is LFSR in the specification. The polynomial for the scrambler generator is

$$g(X) = 1 + X^{14} + X^{15}, \quad (2)$$

where X is a single chip delay T_c. By the given generator polynomial, the corresponding scrambler output is generated as

$$S_n = S_{n-14} \oplus S_{n-15}, \qquad n = 0,1,2,\ldots \quad (3)$$

where $\oplus$ denotes modulo-2 addition. Each user shall use a distinct assigned pulse shift pattern $h^{(k)}$, which represents the TH sequence, to eliminate the catastrophic collisions in multiple-user environment. These TH sequence are pseudo-random with single chip delay T_c. Therefore the TH sequence provides an additional time shift to every pulse for a specific user. In the BPM modulation, a *k*th pulse is shifted to $h^{(k)}T_c$ seconds, which is a discrete value in the range of $(0 \le h^{(k)} \le N_{hop} - 1)\,T_c$ seconds.

2.3 Channel Model for IEEE 802.15.4a

The IEEE 802.15.4a UWB channel is modified SV-model, and defines nine sets of parameters for different environments using Nakagami-distribution for small-scale fading with various m-factors for distinct components. We use channel model 1 (CM1) in the simulation, which stands for indoor residential environment with line-of-sight (LOS) covering the frequency range from 2 to 10 GHz[8].

For large scale fading, the distance dependence of the pathloss model in dB scale is described by

$$PL(d) = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + S, \qquad (4)$$

where the reference distance d_0 is set to 1 m, and PL_0 is the pathloss at the reference distance. n is the pathloss exponent, which also depends on the environment and on whether a LOS connection exists between the transmitter and receiver or not. Shadowing S is defined as the variation of the local mean around the pathloss, where S is a Gaussian-distributed random variable with zero mean and standard deviation σ_S. On considering AWGN scenario, the standard deviation σ_S is equal to 3.7 as the distance is tens of meters[9].

Ⅲ. Novel Multiple Access Scheme for Low-Rate IR-UWB

The multiple access capability of TH spread spectrum signals is acquired in the same way as that of the frequency-hopping signals, namely by making the possibility of multiple-user's transmissions in the same time slot lower. In the case of TH, all transmissions are in the same frequency band, thus the probability of more than one transmission in the same time increases. This is avoided by assigning distinct TH sequences to different users, such as the application of m-sequence in IS-95 and gold sequence in WCDMA respectively. Also there is an orthogonal gold sequence with better cross-correlation value and more balance properties compared with that of gold sequence. We make a use of these sequences in the IEEE 802.15.4a to improve the performance of multiple-access. On the other hand, the Number of TH positions in BPM modulation is considered to be increased, which is 32 in maximum in the specification.

3.1 M-sequence

M-sequence is generated by a single linear shift register. In particular, a sequence with the maximum possible period, ($N_m = 2^n$-1), is generated by an n-stage binary shift register with linear feedback. We choose 13 ($N_m = 2^{13}$-1 = 8191) stages linear shift register to generate m-sequence in the simulation due to the practical Number of data transmitted. The order is 6 as considering maximum 2^6 = 64 TH positions. Hence if the data length is 1200 with one bit per symbol, the sequence length needs to be more than 7200. We construct m-sequence m_1 by the generator polynomial given below

$$g_{m1}(X) = 1 + X^4 + X^5 + X^7 + X^9 + X^{10} + X^{13}. \qquad (5)$$

Then the initial values of all ones are assigned to the registers[10,11].

3.2 Gold sequence

The m-sequence has good autocorrelation characteristics. However the Number of m-sequences that have same code length and the same correlation properties is limited. When many users communicate to each other is realized, we need sequences with much more distinct codes that have the same correlation value. Thus gold sequence is a better choice contained $N_g = 2^n$+1 codes (plus the two m-sequences), which is generated by exclusive (EX) *OR* of two m-sequences whose relationship is a preferred pair. Here another m-sequence m_2 is constructed by the generator polynomial

$$g_{m1}(X) = 1 + X^5 + X^6 + X^7 + X^8 + X^{12} + X^{13}, \quad (6)$$

with initial values [1001111111100]. Thus the gold sequence is generated by *EXOR* between m_1 and m_2, which make up of a preferred pair.

3.3 Orthogonal gold sequence

The gold sequence has many distinct codes compared to those of the m-sequences. However, there are several problems such as: the proportion of 0 to 1 is not always balanced; the cross-correlation value of the gold sequence is not 0 in a synchronized environment the code length is an odd number. As a result, to solve the above issues, one chip is added to the gold sequence to balance the ratio of 0 and 1. The cross-correlation value of the orthogonal gold sequence is 0 at the synchronous point. At other points, the characteristics of the sequence are similar to those of gold sequence. In fact, 2^n orthogonal gold codes can be obtained by this simple zero padding. The implementation is very simple for hardware realization as well as software realization.

3.4 Increased the Number of TH Positions

On the other hand, in order to lessen the catastrophic collisions, the Number of TH positions in BPM modulation is considered to be increased, which is 32 in maximum in the specification. We believe that can make a boost on the performance. Here the Number of TH positions is assigned as 64.

Ⅳ. Simulation Results and Performance Evaluation

Computer simulations have been run to assess the performance of our novel multiple access scheme considered both various types of TH sequences and the Number of TH positions. The channel statistics reflects the model CM1 in [8], which is based on measurements that cover a range of 7-20 m and characterizes indoor residential LOS environments. The monocycle is compliant with the IEEE 802.15.4a proposed standard and has the shape of raised-cosine pulse. The data rate is 0.87 Mbps because we only consider $RS_6(63.55)$ encoding with coding rate 0.87 excluded the convolutional code. In the receiver side, we apply an energy detection receiver with weighted energy detection[12] and a perfect synchronization is assumed. For a clear measurement, we name the sequence in the specification as SS, m-sequence as MS, gold sequence as GS and orthogonal gold sequence as OGS. The performance metrics is BER.

In Fig. 1, the BER performance of IR-UWB multiple access with distinct TH sequences only considered 2 users is presented. The code shift for MS, GS and OGS are $2^{13}/n$ (n is the number of users), while the code shift is 1 for SS. We can clearly discern that all the sequences (MS, GS and OGS) that we suggested have better performances than that of SS. Also OGS achieves the best performance at 16 dB as a result of better orthogonal property compared to those of MS and GS. However, all of them reach to error floors due to the inevitable collisions.

So as to mitigate the effects of collisions, we can improve it way by raising the Number of TH positions in BPM as mentioned above. Fig. 2 shows the BER performance with 64 TH positions, which we double the maximum size in the specification. It is clear we achieve a remarkable improvement that the OGS curve reaches the BER of 10^{-5}, while the MS and GS lines attain the BER of 10^{-4}.

Also we present the BER performances when the Number of users is increased. In Fig. 3, the scenarios of

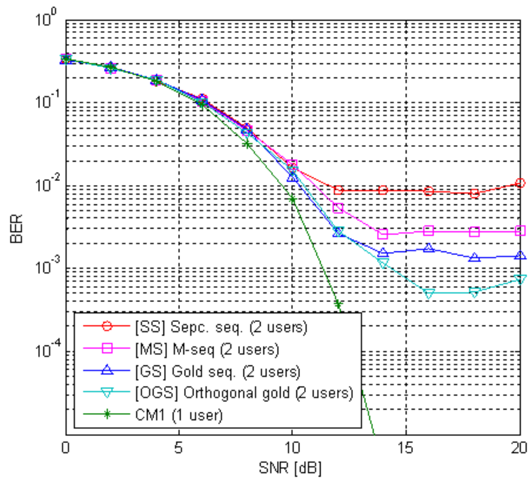

Fig. 1. 2 users' BER performance of IR-UWB with different TH sequences in CM1 (32 TH positions)

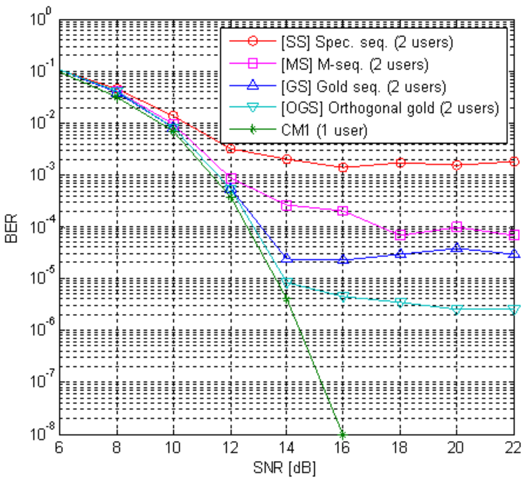

Fig. 2. 2 users' BER performance of IR-UWB with different TH sequences in CM1 (64 TH positions)

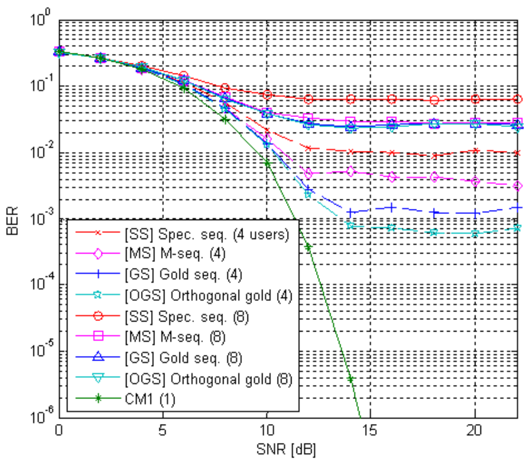

Fig. 3. 4 & 8 users' BER performance of IR-UWB with different TH sequences in CM1 (64 TH positions)

4 and 8 users are shown. As a result of the catastrophic collisions, the performance of MS, GS, OGS are almost the same, which is still a little better than that of SS in the case of 8 users.

V. Conclusions

In this paper, a novel multiple access scheme with both various TH sequences and increased the number of TH positions is derived. The proposed methods make a significant improvement for the performance of IEEE 802.15.4a IR-UWB system against MUI, especially when the maximum TH positions are doubled. However there is still much work to do to eliminate the existing error floor caused by the catastrophic collisions.

References

〔1〕 IEEE Standard 802.15.4a, IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements, Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs), Mar. 2007.

〔2〕 Zahra Ahmadian and Lutz Lampe, "Performance analysis of the IEEE 802.15.4a UWB system," *IEEE Trans. Commun.*, Vol.57, No.5, pp.1474-1485, May 2009.

〔3〕 M. Flury, R. Merz, J.-Y. Le Boudec, and J. Zory, "Performance evaluation of an IEEE 802.15.4a physical layer with energy detection and multi-user interference," in *Proc. IEEE Intl. Conf. Ultra-Wideband (ICUWB)*, Sep. 2007, pp.663-668.

〔4〕 Hong Zhang, SungHyun Hong, and KyungHi Chang, "Performance evaluation of 802.15.4a UWB system with non-coherent receiver," in *Proc. KICS conference*, Nov. 2009. Session 7C-27.

〔5〕 Moe Z. Win and Robert A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless-access communications," *IEEE Trans. Commun.*, Vol.48, pp.679-691, Apr. 2000.

〔6〕 Bo Hu and Norman C. Beaulieu, "Accurate evaluation of multiple-access performance in TH-PPM and TH-BPSK UWB systems," *IEEE Trans. Commun.*, Vol.52, pp.1758-1766, Oct. 2004.

〔7〕 Moe Z. Win and Robert A. Scholtz, "Impulse radio: how it works," *IEEE Commun. Lett.*, Vol.2, No.2, pp.36-38, 1998.

〔8〕 A. F. Molisch, B. Kannan, C.-C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H.

Schantz, U. Schuster, and K. Siwiak, “IEEE 802.15.4a Channel Model-Final Report,” IEEE 802.15-04-0662-00-004a, 2005.

〔9〕 A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2005.

〔10〕 R. Tanner and J. Woodard, *WCDMA Requirements and Practical Design*, Wiley, 2002.

〔11〕 H. Harada, R. Prasad, *Simulation and Software Radio*, Artech House, 2002.

〔12〕 Z. Tian and B. Sadler, “Weighted energy detection of ultra-wideband signals,” in *Proc. IEEE SPAWC 05*, June 2005, pp.1068-1072.

휘 빙 (Bing Hui) 정회원

2005년 7월 중국 동북대학교 정보통신공학과 공학사

2009년 8월 인하대학교 정보통신 대학원 공학석사

2009년 9월~현재 인하대학교 정보통신 대학원 박사과정

<관심분야> OFDM / MIMO Systems, MIMO Detection algorithm, WiMAX, 3GPP LTE

장 홍 (Hong Zhang) 준회원

2007년 7월 중국 지린대학교 컴퓨터공학과 공학사

2008년 9월~현재 인하대학교 정보통신 대학원 석사과정

<관심분야> RFID / USN, Multi-hop Relaying Systems, Low-rate UWB

장 경 희 (KyungHi Chang) 종신회원

1985년 2월 연세대학교 전자공학과(공학사)

1987년 2월 연세대학교 전자공학과(공학석사)

1992년 8월 Texas A & M Univ., EE Dept.(Ph.D.)

1989년~1990년 삼성종합기술원 주임연구원

1992년~2003년 한국전자통신연구원, 이동통신연구소 무선전송방식연구팀장(책임연구원)

2003년~현재 인하대학교 정보통신대학원 교수

<관심분야> 4세대 이동통신 및 3GPP LTE 무선전송방식, WMAN 및 DMB 시스템 무선전송기술, Cognitive Radio, Cross-layer Design, Cooperative Relaying System, RFID / USN Systems, Mobile Ad-hoc Network, 해상/수중 통신 등