

A Complementary Code-CDMA-Based MAC Protocol for UWB WPAN System

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We propose a new multiple access control (MAC) protocol based on complementary code-code division multiple access (CC-CDMA) technology to resolve collisions among access-request packets in an ultra-wideband wireless personal area network (UWB WPAN) system. We design a new access-request packet to gain higher bandwidth utilization and ease the requirement on system timing. The new MAC protocol is energy efficient and fully utilizes the specific features of a UWB WPAN system, thus the issue of complexity caused by the adoption of CDMA technology is resolved. The performance is analyzed with the consideration of signal detection error. Analytical and simulation results show that the proposed CC-CDMA-based MAC protocol exhibits higher throughput and lower average packet delay than those displayed by carrier sense multiple access with collision avoidance (CSMA/CA) protocol.

Keywords and phrases: UWB, MAC, CC-CDMA, WPAN.

1. INTRODUCTION

Ultra-wideband (UWB) is the radio technology that can use very narrow impulse-based waveforms to exchange data. The Federal Communications Commission (FCC) requires the impulse waveforms to occupy minimum of 500 MHz of spectrum or a band of spectrum that is broader than 1/4 of the band's center frequency [1]. UWB can provide much higher spatial capacity (bits/s/m²) than any other technology, and the technology is typically used for transmitting high-speed, short-range (less than 10 meters) digital signals over a wide range of frequencies. This makes UWB attractive as a high data rate physical layer for wireless personal area network (WPAN) standards.

UWB-based physical (PHY) layer radio technology can be divided into two groups: single band and multiband [1]. Two commonly used single-band impulse radio systems are time-hopping spread-spectrum impulse radio (TH-UWB) and direct-sequence spread-spectrum impulse radio

(DS-UWB). Multiband UWB (MB-UWB) divides the whole spectrum into several bands that are at least 500 MHz, it gives low interpulse interference but high data rates by using orthogonal frequency division multiplexing (OFDM) technology. MB-OFDM and DS-UWB were proposed for the physical layer for IEEE 802.15.3 Task Group 3a [2, 3].

The main objective of the medium access control (MAC) layer in UWB system is to perform the coordination function for the multiple-channel access. In recent years, more and more research in UWB has focused on MAC protocol design to fully exploit the flexibility offered by the UWB. Initially the IEEE 802.15.3 MAC protocol [4], which is designed to support additional physical layers such as UWB, is to be applied. Several industries and companies have decided to map their UWB technology onto IEEE 802.15.3 MAC protocol. However, it is found that IEEE 802.15.3 MAC protocol is not ideal when applied to UWB WPAN, due to the use of carrier sense multiple access with collision avoidance (CSMA/CA) as the channel access mechanism. CSMA/CA is not efficient in UWB WPAN because of the following reasons [5, 6, 7, 8]:

- (i) the power consumed in idle listening is significant,
- (ii) voice and video cannot cope with too large transmission delays and jitter,

- (iii) using ready-to-send/clear-to-send (RTS/CTS) handshakes and the possibility of collisions drastically affect the performance in ad hoc environments.

Aloha-based channel access protocol is proposed in [1], but the contention problem during the channel access period cannot be resolved. System performance is still degraded by packet collisions, and quality of service (QoS) support becomes difficult.

In this paper, we propose a complementary code-code division multiple access (CC-CDMA)-based MAC protocol for UWB WPAN system. The protocol is similar to the IEEE 802.15.3 MAC protocol, but using CC-CDMA as the channel access protocol to completely avoid packet collisions. Consequently, traffic scheduling becomes an easy task and QoS can be conveniently managed.

Recently, Li [9] presented a method based on CC-CDMA to design access-request packets. Our channel access-request packet is similar to the work in [9], but differs by how users are identified and when they can begin transmission. In [9], users are identified by different delays, which demands that each user is assigned a special time to send authentication request during the access period. In the protocol proposed in this paper, users are identified by different phase offsets of the complementary code (CC), and all users can send authentication request at the beginning of the access period instead of assigning a special beginning time to each user. Thus, the timing control mechanism in our protocol is much simpler compared to that in [9]. Theoretical analysis and simulation results show that our protocol can gain higher bandwidth utilization and higher spreading gain than those of [9].

The paper is organized as follows. Section 2 gives an overview of IEEE 802.15.3, and presents the MAC basic principles for an UWB WPAN. Section 3 introduces the proposed CC-CDMA-based MAC protocol, which is then analyzed in Section 4. Simulation results are shown in Section 5 to validate the results of theoretical analysis. Finally, Section 6 concludes the paper.

2. BACKGROUND

2.1. IEEE 802.15.3 MAC protocol

The 802.15.3 MAC mainly works within a piconet. A piconet is defined as a small network, which allows a small number of independent data devices (DEV) to communicate with each other in short range. One DEV is required to be the piconet coordinator (PNC). The PNC provides the basic timing and information for a piconet. The 802.15.3 timing within a piconet is based on the superframe. The time-slotted superframe includes three parts: a beacon, a contention access period (CAP) and a channel time allocation period (CTAP), which are illustrated in Figure 1.

The beacon frame is sent by the PNC at the beginning of a superframe, and contains the system timing and other control information. During a CAP, the DEVs access the channel using CSMA/CA to send commands and nonstream asynchronous data. Channel access in the CTAP is based on TDMA. The CTAP is divided into channel time allocation

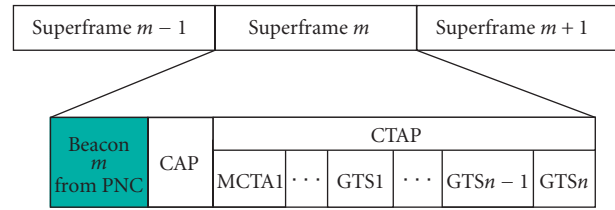


FIGURE 1: 802.15.3 superframe format.

(CTA) slots, and CTAs are allocated to DEVs by the PNC. CTAs used for asynchronous and isochronous data streams are called guaranteed time slots (GTSs). CTAs used for communication between DEVs and the PNC are called management channel time allocation (MCTAs). MCTAs can be divided into three types: association MCTAs, open MCTAs, and regular MCTAs. Open MCTAs and regular MCTAs are used by the DEVs associated to the piconet to exchange control messages with the PNC. Open MCTAs enable the PNC to service a large number of DEVs by using a minimum number of MCTAs. When there are few DEVs in a piconet it might be more efficient to use MCTAs assigned to a DEV, called regular MCTAs. Association MCTAs are used by unassociated DEVs to send the request to associate to the piconet. Slotted Aloha is used to access open and association MCTAs. The access mechanism for regular MCTAs is TDMA [1, 4].

2.2. MAC principles for UWB WPAN

A WPAN is distinguished from other types of wireless data networks in that communications are normally confined to a person or object that typically covers about 10 meters. In this network, the role of the MAC protocol is to coordinate transmission access to the channel, which is shared among all nodes. General requirements that apply to the MAC protocol in WPAN are [10, 11]:

- (i) energy constrained operation is of the utmost importance in WPAN,
- (ii) simple control mechanism is needed to increase efficiency and save power,
- (iii) flexibility, fast changing topologies, caused by new nodes arriving and others leaving the network,
- (iv) limiting the interference between links so that the spectrum can be used efficiently.

Therefore, power conservation is one of the most important design considerations for MAC protocol in WPAN, and the major energy waste comes from idle listening, retransmission, overhearing, and protocol overhead. Thus, to make MAC protocol energy efficient, the following design guidelines must be obeyed [12]:

- (i) minimize random access collision and the consequent retransmission,
- (ii) minimize idle listening (the energy spent by idle listening is 50%–100% of that spent while receiving),
- (iii) minimize overhearing,
- (iv) minimize control overhead,
- (v) explore the trade-off between bandwidth utilization and energy consumption.

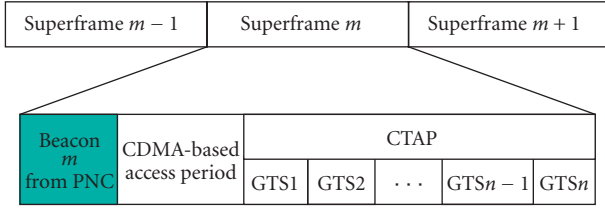


FIGURE 2: Proposed superframe format for CC-CDMA protocol.

The proposed CC-CDMA-based MAC protocol satisfies most of the above guidelines. Packet collision is completely avoided. Idle listening and overhearing are not needed. Using CDMA technology can fully utilize the bandwidth of a UWB system to save energy. Finally, the control mechanism is simple compared to that in traditional CDMA cellular system.

3. THE NEW CC-CDMA MAC PROTOCOL

3.1. Protocol description

Similar to IEEE 802.15.3, our MAC protocol timing within a piconet is based on the superframe divided into three zones, which is illustrated in Figure 2:

- (i) beacon frame, emitted by the PNC to synchronize DEVs and broadcast information about the piconet characteristics and the resource attribution,
- (ii) unlike the 802.15.3, we change the CAP to a CC-CDMA-based contention free access period. Acknowledgement for this phase is done in the beacon of the next superframe,
- (iii) a period during which DEVs are allocated CTAs by the PNC to transmit data frames.

Each associated DEV is assigned a spreading code by the PNC. In the access period, DEVs can send their channel time requirements and other messages to the PNC based on CDMA technology. Another special spreading code is assigned for unassociated DEVs to send to the PNC the request to associate to the piconet. Thus the MCTAs in 802.15.3 are not needed.

The use of a CC-CDMA contention free access period requires the design of access-request packets that are completely orthogonal at the receiver, thus eliminating mutual interference. In our proposed protocol, all DEVs in a piconet are using a single spreading code. As such, DEVs are distinguished only by the relative phase shift of the code. Thus, the receiver circuitry is relatively simple.

3.2. Access-request packet design

Complementary codes are characterized by the property that their periodic autocorrelative vector sum is zero everywhere except at the zero shift. We define N as the spreading factor, which is equal to the length of the code. Given a pair of complementary sequences with $A = [a_0 a_1 \dots a_{N-1}]$ and

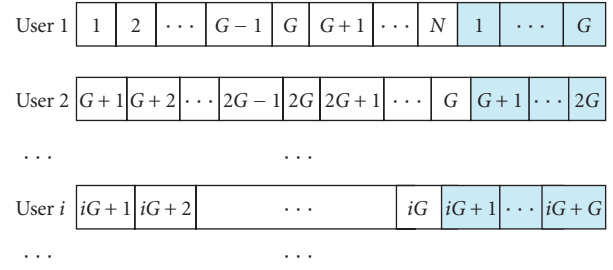


FIGURE 3: Code assignment.

$B = [b_0 b_1 \dots b_{N-1}]$, the respective autocorrelative series are given by [13]

$$c_j = \sum_{i=0}^{N-1} a_i \cdot a_{i+j}, \quad (1)$$

$$d_j = \sum_{i=0}^{N-1} b_i \cdot b_{i+j}.$$

Ideally, the two sequences are complementary if

$$c_j + d_j = \begin{cases} 2N, & j = 0, \\ 0, & j \neq 0. \end{cases} \quad (2)$$

Consider a piconet, where the number of active users is K . Assume that the transmission is asynchronous, near-far with frequency selective fading. Channels are assumed time invariant within each access-request slot. Assume that the maximum channel propagation delay of user i is L_i , and user i begins transmission after a delay D_i . We define an integer G satisfying

$$G \cdot T_c > \max(L_i) + \max(D_i), \quad (3)$$

where T_c is the chip period of the complementary code. We call G the guard length. Hence, the spreading code of each user is designed as in Figure 3.

The number in each box of Figure 3 denotes the corresponding chip of the CC, and the spreading factor in our system is $N + G$. Thus, if G satisfies (3), we can assure that the relative phase shift of the received CC of any two different DEVs at the PNC is nonzero. By defining these code assignments, each DEV can send authentication request at the beginning of the access period. In [9], DEVs are identified by different delays, which demands that each DEV must obtain the beginning of the access period and calculate the special time assigned to it to send authentication request. Thus, our timing mechanism is much simpler than that in [9].

In order to eliminate the multiaccess interference (MAI), the received signals at the PNC must be orthogonal, which can be obtained by defining the proper correlative zone at the receiver in our protocol. The correlative zone can be selected as in Figure 4. The start of the first data symbol period is equal to the beginning of access period. The duration of

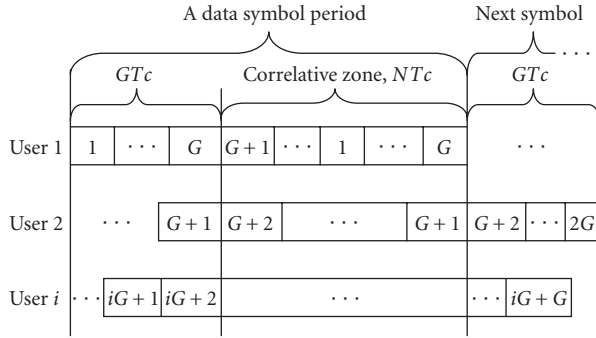


FIGURE 4: The correlative zone at the receiver. (To simplify the analysis, we assume the total delay of user 1 is zero.)

one data symbol period is $(N + G)T_c$, and the propagation delay of each user is less than GT_c . Thus, the first GT_c period of each symbol may interfere with the previous symbols of other users, but the last NT_c period of each symbol is free of intersymbol interference, and the relative chip shift of any two users' complementary codes is nonzero. Since the correlative zone includes an entire CC period, all users' signals in the correlative zone are orthogonal, and the processing gain in our system is still N .

3.3. Length of the access-request packet

High spreading factor means high processing gain, but less efficiency and more complication. The main purpose of using CDMA technology here is to provide many orthogonal channels. Also, reducing access-request packet length achieves energy savings, hence the shortest length of the access-request packet is desired.

Define LRP as the length of access-request packet. From Section 3.2, the LRP of our protocol is

$$\text{LRP} = N + G. \quad (4)$$

In order to provide K orthogonal channels, N must satisfy

$$N \geq K \cdot G. \quad (5)$$

Thus $\text{LRP} \geq K \cdot G + G$. From [9], the length of access packet is $\text{LRP}' = (K - 1) \cdot G + N'$, where N' is the length of the complementary code, which must satisfy $N' > G$, otherwise the system becomes a TDMA system. Assuming $G = 2$, the LRP of CC-CDMA protocol and the protocol in [9] are shown in Figure 5. It is seen from Figure 5 that the CC-CDMA protocol is more efficient when $N' > 4$.

As seen from (5), the length of access-request packet for the CC-CDMA protocol is directly related to the number of users (K), which is dynamic in a piconet. Thus, it is important for the PNC to assign complementary code of different lengths according to the number of users. One simple way to realize a variable length complementary code is using zero insertion technology [14]. As illustration, given a pair of

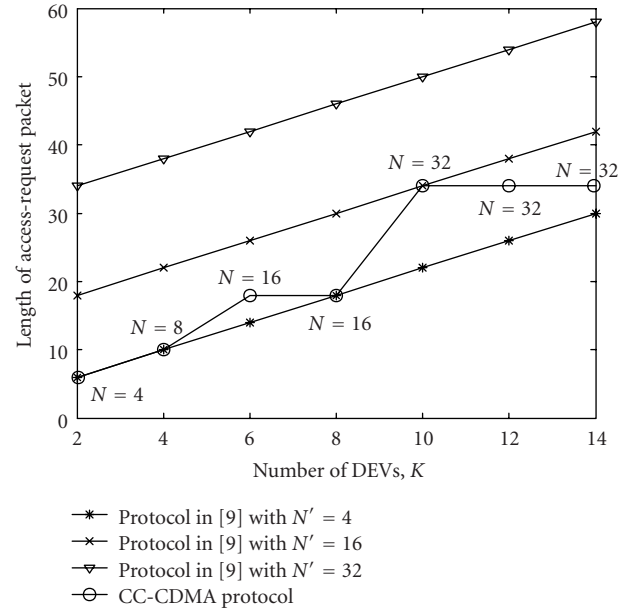


FIGURE 5: LRP of CC-CDMA protocol and protocol in [9].

complementary codes

$$\begin{aligned} A &= [-1, -1, -1, +1, +1, +1, -1, +1], \\ B &= [-1, -1, -1, +1, -1, -1, +1, -1], \end{aligned} \quad (6)$$

we can insert zeros periodically in A and B to make a new pair of codes. For example, with one zero insertion, the new codes are

$$\begin{aligned} A' &= [-1, 0, -1, 0, -1, 0, +1, 0, +1, 0, +1, 0, -1, 0, +1, 0], \\ B' &= [-1, 0, -1, 0, -1, 0, +1, 0, -1, 0, -1, 0, +1, 0, -1, 0]. \end{aligned} \quad (7)$$

It is easy to prove that the new codes still satisfy the autocorrelative property of CC.

Proof. Assume a code $c = [c_0 c_1 \dots c_{N-1}]$, and the autocorrelation of the code satisfies

$$\sum_{i=0}^{N-1} c_i \cdot c_{i+j} = \begin{cases} N, & j = 0, \\ 0, & j \neq 0. \end{cases} \quad (8)$$

If we insert k zeros periodically in c to make a new code c' , thus the elements in c' satisfy

$$c'_i = \begin{cases} 0, & i \neq m \cdot (k + 1), \\ c_{m+1}, & i = m \cdot (k + 1), \end{cases} \quad m = 0, 1, \dots, N - 1. \quad (9)$$

The length of the new code is $N \cdot (k + 1)$. From (9) we can see that if $j \neq m \cdot (k + 1)$, then one of c'_i and c'_{i+j} must be zero, where $i = 0, \dots, (k + 1) \cdot N - 1$. Now, c'_i and c'_{i+j} are

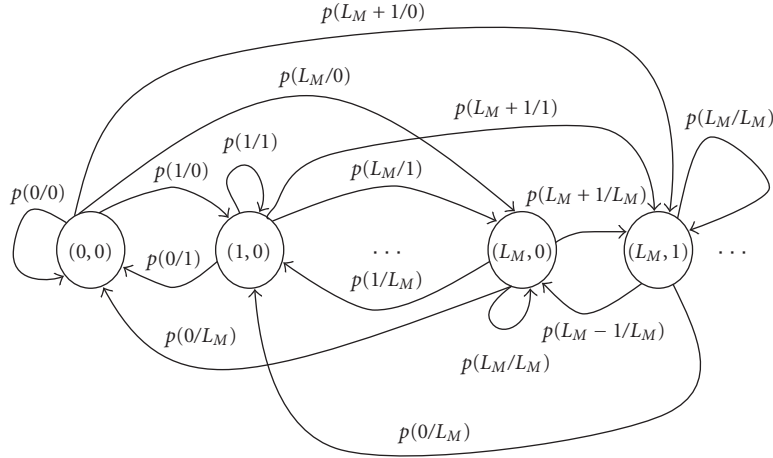


FIGURE 6: Markov chain for the system without detection error.

nonzero only if $j = m \cdot (k + 1)$ and $i = n \cdot (k + 1)$, where $n = 0, \dots, N - 1$. Thus,

$$\begin{aligned} & \sum_{i=0}^{(k+1) \cdot N - 1} c'_i \cdot c'_{i+j} \\ &= \begin{cases} 0, & j \neq m \cdot (k + 1), \\ \sum_{n=0}^{N-1} c_i \cdot c_{i+m}, & j = m \cdot (k + 1), \end{cases} \quad m = 0, \dots, N - 1, \end{aligned} \quad (10)$$

the autocorrelation of code c' satisfies

$$\sum_{i=0}^{(k+1) \cdot N - 1} c'_i \cdot c'_{i+j} = \begin{cases} 0, & j \neq 0, \\ N, & j = 0. \end{cases} \quad (11)$$

□

Although using zero insertion technology is a simple way to realize a variable length complementary code, the drawback is that the processing gain does not increase as the length of the code increases.

4. PERFORMANCE ANALYSIS

This section presents performance analysis of the proposed CC-CDMA-based MAC protocol. The objective of analysis is to derive expressions for system throughput, average packet delay, and duration of access period. Our analysis approach follows that used in [9]. Note that the analysis presented in [9] assumes unlimited frame length. In contrast, the analysis presented in this paper assumes limited frame length, which is a more realistic and practical assumption.

4.1. System throughput

System throughput is defined as the fraction of the channel capacity used for data transmission. Let the length of data

packet slots and access-request slots be L_d and L_a , respectively, and we assume $L_d = L_a$ to simplify the analysis. The traffic load is Poisson-distributed with average λ_u packets per slot per user. Then, the overall average traffic load is $\lambda = K \cdot \lambda_u$ packets per slot, where K is the number of active users. We denote the maximum length of data packet slots in a super-frame by L_M , and the buffer size is infinite.

We first consider the case without detection error. Assume that there are j data packet slots in frame n , and $0 \leq j \leq L_M$. Then the probability that there are i newly generated data packets is [9]

$$p(i|j) = \frac{[(j+1)\lambda]^i}{i!} e^{-(j+1)\lambda}. \quad (12)$$

In order to analyze the system behavior, we construct a Markov chain with a state pair (S, R) , where S denotes the number of data packets sent in current frame, and R denotes the number of surplus data packets in the buffer at the time of sending a frame. Therefore, the state transition probability from state (S_1, R_1) to state (S_2, R_2) can be expressed as

$$\begin{aligned} & T_p((S_2, R_2) | (S_1, R_1)) \\ &= \begin{cases} p(S_2 + R_2 - R_1 | S_1), & R_1 \leq S_2 + R_2, \\ 0, & R_1 > S_2 + R_2, \end{cases} \end{aligned} \quad (13)$$

where $p(i|j)$ is calculated by (12). The Markov chain is shown in Figure 6.

Since the proposed protocol is collision free, and without detection error, the average throughput of the system is

$$R = \frac{\sum_{j=0}^{L_M-1} j L_d P_{j,0} + L_M L_d P_{L_M}}{\sum_{j=0}^{L_M-1} (j L_d + L_a) P_{j,0} + (L_M L_d + L_a) P_{L_M}}, \quad (14)$$

where $P_{L_M} = \sum_{k=0}^{\infty} P_{L_M,k}$, and the state probability $P_{j,k}$ is calculated by solving a system of linear equations obtained from the Markov chain in Figure 6.

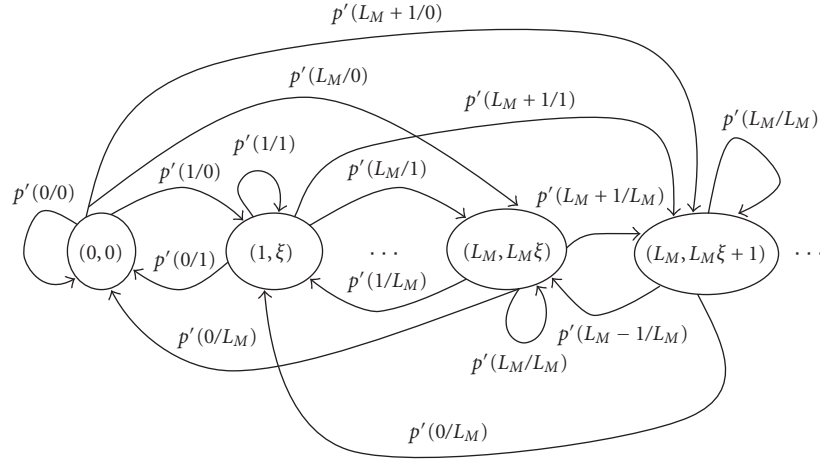


FIGURE 7: Markov chain for the system with detection error.

Next, we consider the case with detection error. We assume P_{e1} is the detection error rate (DTR) of failed detection, P_{e2} is the DTR of false alarm, and they are independent of each other. Thus, the state transition probability can be approximated as [9]

$$p'(i|j) = p\left(\frac{(i-j \cdot P_{e1})(1-P_{e2})}{1-P_{e1}} \middle| j\right), \quad (15)$$

and $p'(i|j) = 0$ when $(i-j \cdot P_{e1}) < 0$. The Markov chain in Figure 6 must be modified to calculate $P_{j,k}$ with detection error. If we define $\xi = P_{e1}(1-P_{e2})/(1-P_{e1})$, the modified Markov chain is shown in Figure 7.

Thus, the modified state probabilities $P'_{j,k}$ are calculated from the modified Markov chain, and the expression for throughput becomes

$$R' = \frac{\left(\sum_{j=0}^{L_M-1} jL_d P'_{j,0} + L_M L_d P'_{L_M}\right) \cdot (1-P_{e2})}{\sum_{j=0}^{L_M-1} (jL_d + L_a) P'_{j,0} + (L_M L_d + L_a) P'_{L_M}}, \quad (16)$$

where $P'_{L_M} = \sum_{k'=0}^{\infty} P'_{L_M, k'}$, $k' = L_M \cdot P_{e1} \cdot (1-P_{e2}) / (1-P_{e1}) + k$.

4.2. Average packet delay

Medium access delay is defined as average time spent by a packet in the MAC queue. It is a function of access protocol and traffic characteristics. In general, the total delay for a message can be broken down into four terms [15]: the service time of the enable transmission interval (ETI), the total delay due to collision resolution, the total delay associated with actual data transmission, and the delay caused by the collision of a data packet in a data slot. The latter term appears when more than one DEV transmit their packets using free access rule in the same slot.

In the proposed CC-CDMA protocol, collisions among data packets are avoided when there is no detection error. Thus, the delay due to collision resolution and the delay caused by the collision of a data packet are zero. Consequently, we only need to analyze the delay associated with actual data transmission and ETI service time.

We first consider the case without detection error. The total delay of data packet transmission equals $0 + 1 + \dots + (j-1) = j \cdot (j-1)/2$ data slots [9], where j is the number of data packet slots in a frame. Due to the finite length of data slots in a frame, there are k data packets that will be transmitted in the following frames, thus the analysis becomes more involved. The ETI service time represents the time each data packet has to wait from when it arrives in the system until it is transmitted, which is determined by the current state and the number of newly generated packets. The average packet delay equals the average number of waiting slots plus two (the access-request slot and the transmission slot in the frame it is transmitted). The average delay is obtained as

$$T = \frac{T_Delay}{\sum_{j=0}^{L_M} \sum_{k=0}^{\infty} j \cdot P_{j,k}} + 2, \quad (17)$$

where T_Delay is the average number of waiting slots. The algorithm for calculating T_Delay is described in the appendix.

Now consider the case with detection error. We can use the same algorithm shown in the appendix to calculate the average number of waiting slots, with changes made to some parameters as follows:

- (i) the state transition probability and the state probability need to be recalculated as described in Section 4.1;
- (ii) the number of surplus data packets in the buffer at the time of sending a frame is changed from k to $k' = j \cdot P_{e1} \cdot (1-P_{e2}) / (1-P_{e1}) + k$;
- (iii) the number of successfully transmitted data packets reduces to $j \cdot (1-P_{e2})$;
- (iv) the number of newly generated packets is changed from i to $i' = i \cdot (1-P_{e2}) / (1-P_{e1}) - k'$. When $i > L_M$, $i' = L_M \cdot (1-P_{e2}) / (1-P_{e1}) + (i-L_M) - k'$.

Thus, the average delay can be obtained as

$$T' = \frac{T_Delay'}{\sum_{j=0}^{L_M} \sum_{k=0}^{\infty} j \cdot (1-P_{e2}) \cdot P'_{j,k}} + 2, \quad (18)$$

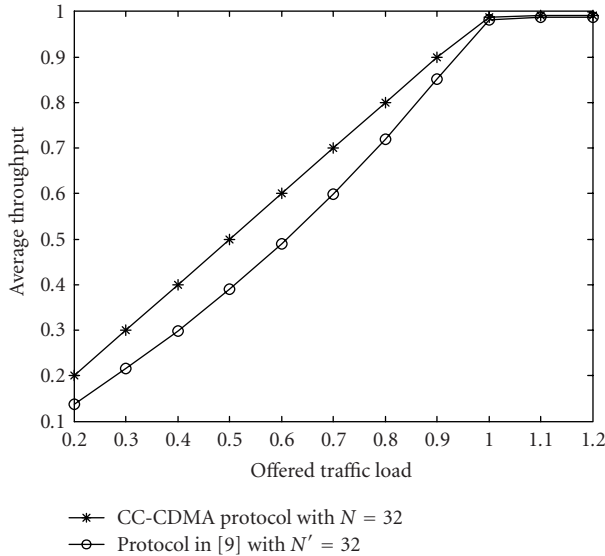


FIGURE 8: Throughput performance comparison.

where T_Delay' is calculated by using the new parameters as mentioned above.

In order to compare the throughput performance of CC-CDMA protocol and the protocol in [9], we assume the total number of states is 128, $G = 2$, $N = 32$, and the number of DEVs is 10. We define $\beta = LRP'/LRP$, so that $\beta = 1.5625$ when $N' = 32$. If we assume $L_d = L_a$ in our protocol, the length of access-request slots in [9] must satisfy $L'_d = \beta \cdot L_a$. The comparison between the throughput performance of the CC-CDMA protocol and the protocol in [9] with infinite frame length is shown in Figure 8, where it is seen that the CC-CDMA protocol is more efficient than that of [9] when $N' = N$.

Numerical results of throughput and delay of CC-CDMA protocol with detection error and limited frame length are shown in Figures 9 and 10, respectively. The results are compared with the corresponding numerical results of the CC-CDMA protocol with infinite frame length. The results shown in Figures 9 and 10 assume $L_d = L_a = 128$, and the maximum number of data slots in a superframe is 63. It is concluded that the limited frame length has little effect on system throughput at low loads, which can also be deduced from equation (14). Data packets transmitted in the next frame will add only one slot to the packet delay, hence the increase in delay caused by limited frame length is small. It is also concluded that P_{e1} does not reduce system throughput but causes only a small increase in delay because of the assumption that all affected users transmit again in the following superframes. P_{e2} reduces system throughput and increases the delay obviously, because $j \cdot P_{e2}$ data packets are wasted in every j data packet.

4.3. Duration of access period

The main difference between the proposed CC-CDMA protocol and IEEE 802.15.3 lies in the channel access mecha-

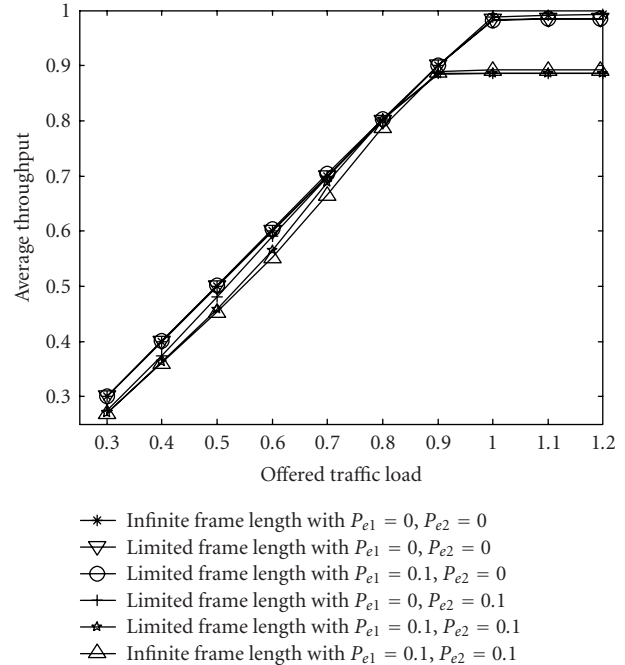


FIGURE 9: Effect of detection error rate on throughput performance.

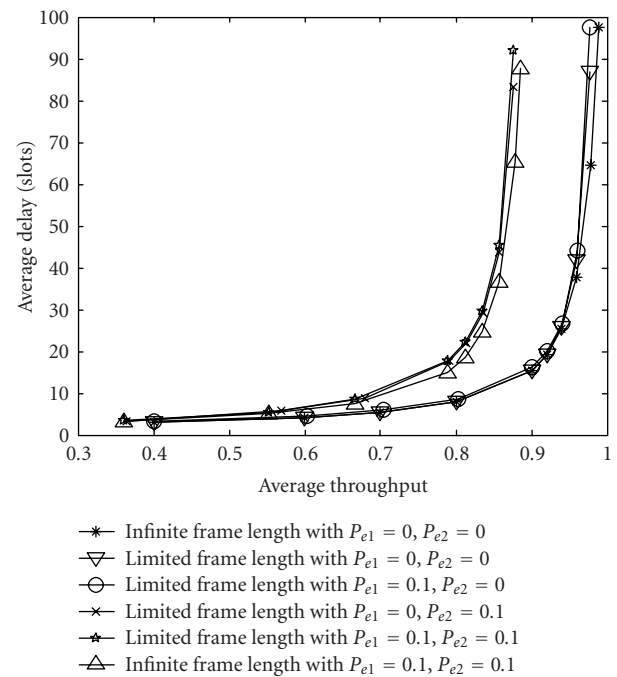


FIGURE 10: Effect of detection error rate on average delay performance.

nism, and we believe the probability of successful channel access and the duration of access period are two important factors for performance comparison. In the proposed CC-CDMA protocol, the probability of successful channel access is 1 considering the case without detection error. Thus, we want to analyze the relationship between the probability of successful access and the duration of access period of

TABLE 1: IEEE 802.15.3 parameters.

Parameters	Values
aSlotTime	10 μ s
τ	1 μ s
ACK	532.7 μ s
RIFS	27.3 μ s
SIFS	10 μ s

CSMA/CA, and compare it with that of the proposed CC-CDMA protocol.

Using CSMA/CA as channel access protocol, the probability that a DEV among K active DEVs can complete a transmission successfully is calculated by [16, 17]

$$P_K(t_s = j) = \prod_{i=1}^{[E(N_j)]+1} \left(\sum_{k=0}^{\text{Idle_Time}/\text{aSlotTime}} P(\text{Idle} = k) \right), \quad (19)$$

where t_s is the duration of access period, $E(N_j)$ is the average number of collisions, $P(\text{Idle} = k)$ is the distribution function of idle period, and Idle - Time is calculated by

$$\text{Idle_Time} = \frac{j - (L_c + \tau + \text{RIFS}) \cdot E(N_j) - L_s}{E(N_j) + 1}, \quad (20)$$

where L_c is the length of collision period (a constant), L_s is the length of transmitting a packet successfully without any collision, τ is propagation delay, and RIFS is retransmission interframe space. Table 1 lists the required parameters of 802.15.3 and the values assumed in the calculations.

We define D_CTR as the duration of channel time request packet and T_R denotes the ratio of the duration of channel time required to complete a transmission successfully and D_CTR. In CC-CDMA protocol, T_R is calculated by

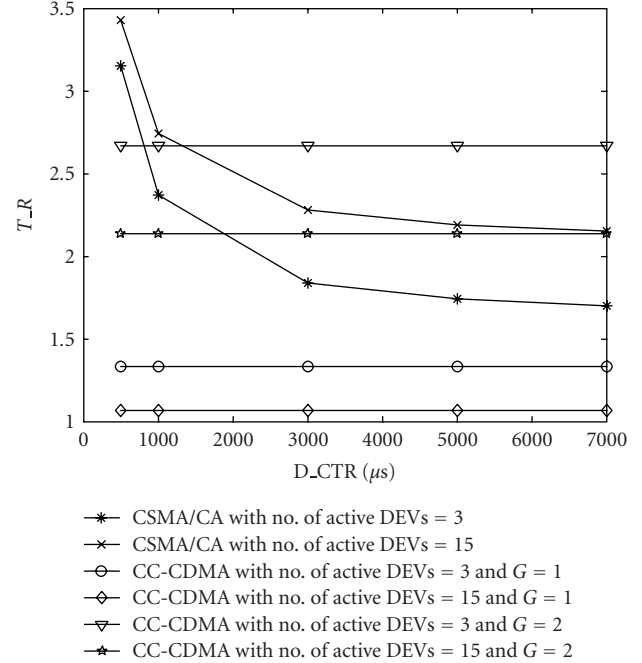
$$T_R = \frac{K \cdot G + G}{K}. \quad (21)$$

When the probability of successful access is near 1 (i.e., $(1 - P_k) < 0.0001$), the relationship between D_CTR and T_R of CSMA/CA and CC-CDMA protocol is shown in Figure 11.

To obtain these results, we assume that the chip rate of CC-CDMA is equal to the data rate of CSMA/CA. We conclude from Figure 11 that the CC-CDMA protocol is more efficient than CSMA/CA when D_CTR is short, the guard length is small, and the number of active DEVs is large.

5. SIMULATION RESULTS

In this section, we first present simulation results to validate the theoretical results of Sections 4.1 and 4.2. Second, we provide simulation results for the probability of successful channel access when the CSMA/CA protocol is used. Finally, we present simulated throughput and packet delay performance for both CC-CDMA and 802.15.3 access protocols.

FIGURE 11: Relationship of T_R and D_CTR.

The following system parameter values are assumed: $L_d = L_a = 128$, the number of DEVs is 10, each DEV has unlimited buffer size, the maximum number of data slots in a superframe is 63, and the detection error rate is zero. The simulation results for average throughput and average delay are shown in Figures 12 and 13, respectively, which display very good match with the analytical results.

The simulation results for probability of successful channel access for the CSMA/CA protocol are shown in Figure 14. The assumptions made in the calculations are (i) every DEV in the system always has packets for transmission, (ii) D_CTR = 1500 microseconds, $L_c = L_s = 2000$ microseconds, and (iii) the duration of access period $t_s = \text{D_CTR} \times \text{LRP}$, where LRP is given by (4). Now, considering the case without detection error when the number of active DEVs is no more than the maximum number calculated using (5), the probability of successful channel access for the proposed CC-CDMA protocol is 100%.

In contrast, for the CSMA/CA protocol, it is observed from Figure 14 that the probability of successful channel access decreases as the number of DEVs increases. Based on the preceding observation, it is concluded that the CC-CDMA protocol is more efficient than CSMA/CA. However, note that the better performance exhibited by CC-CDMA is valid when the guard length is small and the guard length includes some allowance to compensate for synchronous errors. Finally, Figures 15 and 16, respectively, present the average delay and throughput performance of both CC-CDMA and CSMA/CA protocols. It is seen that the proposed CC-CDMA exhibit better performance compared to the CSMA/CA protocol.

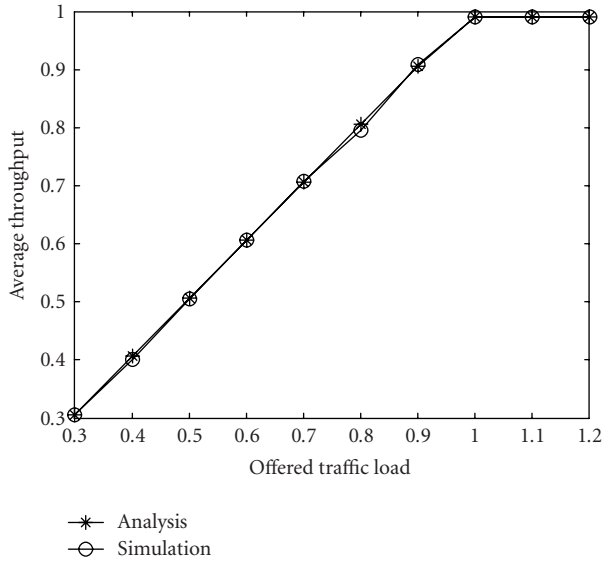


FIGURE 12: Comparison of throughput: analysis versus simulation.

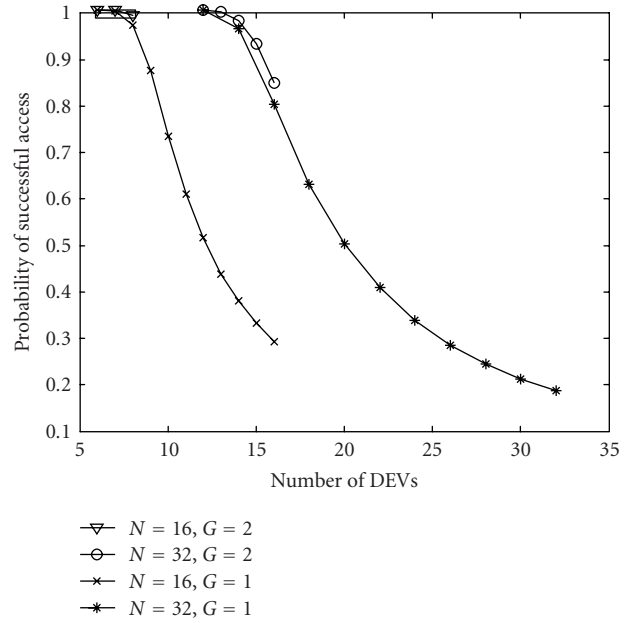


FIGURE 14: The probability of successful access of CSMA/CA.

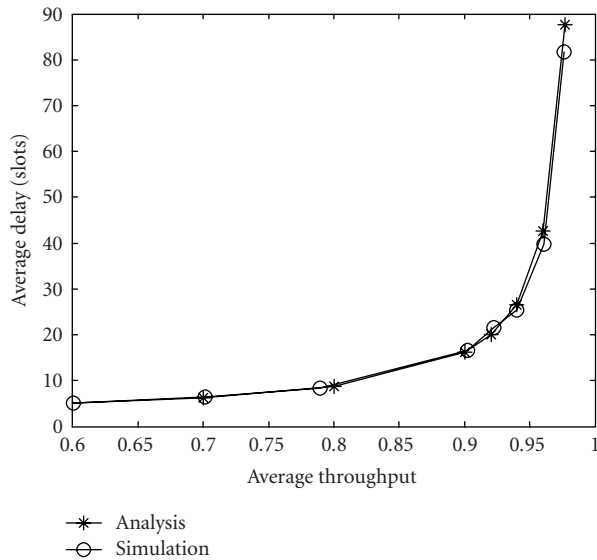


FIGURE 13: Comparison of packet delay: analysis versus simulation.

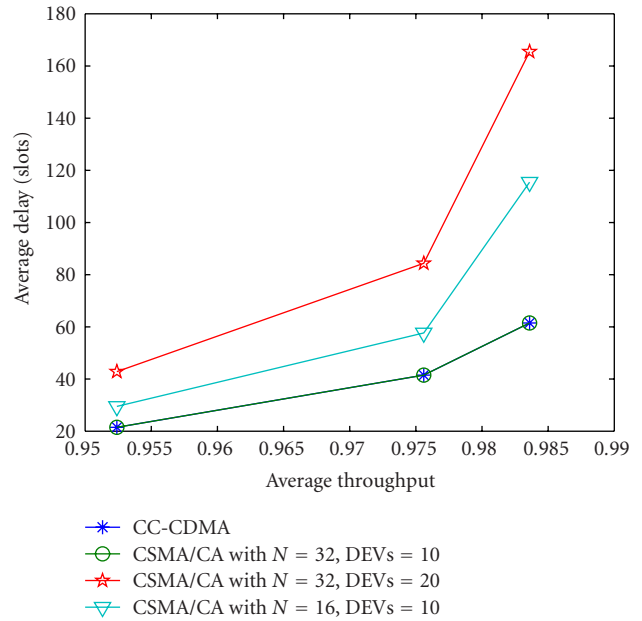


FIGURE 15: Performance of packet delay.

6. CONCLUSIONS

In this paper, we propose a new MAC protocol for a UWB WPAN system. The basic idea is using a CC-CDMA-based channel access protocol to resolve collisions among access-request packets. We design a new access-request packet to gain higher bandwidth utilization and ease the requirement on system timing. Theoretical analysis shows that our access request packet can gain higher bandwidth utilization and higher spreading gain at the same time.

We analyze the system performance of our protocol with limited frame length, which shows that the CC-CDMA protocol achieves throughput almost equal to the offered traffic load up to the maximum value one, with small increase in delay. Compared to CSMA/CA, the length of channel access period of the CC-CDMA protocol is less dependent on the parameters of physical layer and MAC protocol. It is concluded that the CC-CDMA MAC protocol is more efficient when the duration of channel time request packet

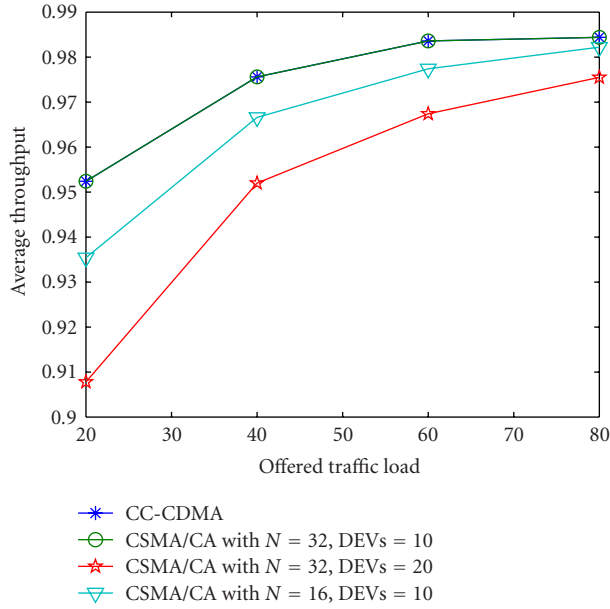


FIGURE 16: Performance of throughput.

is short and the propagation delay is small, which are general requirements in a WPAN system. Analytical and simulation results show that the CC-CDMA protocol has higher throughput and lower average delay than those obtained for the CSMA/CA protocol. Based on these findings, it is concluded that the proposed CC-CDMA protocol is suitable for UWB WPAN system.

APPENDIX

ALGORITHM FOR CALCULATING THE AVERAGE NUMBER OF WAITING SLOTS

To derive the algorithm for calculating the average number of waiting slots, we assume that the newly generated packets are uniformly distributed among slots, the current state satisfies $(S = j, R = k)$, where S denotes the length of data packet slots of current frame, and R denotes the number of surplus data packets in the buffer at the time of sending a frame, and the number of newly generated packets is i . Thus, the algorithm for calculating the average number of waiting slots can be described as in Algorithm 1.

To obtain these results, we assume that the packets generated in an earlier frame are sent first, and the packets generated in the same frame are sent randomly. m_1 and m_2 are defined as follows:

$$\begin{aligned} m_1 &= \text{mod}(k, L_M), & n_1 &= k - m_1 \cdot L_M, \\ m_2 &= \text{mod}(n_1 + i, L_M), & n_2 &= n_1 + i - m_2 \cdot L_M, \end{aligned} \quad (\text{A.1})$$

where $\text{mod}(x, y)$ equals the largest integer less than x/y .

```

T_Delay = 0;
for (j, k) = (0, 0) : (L_M, ∞)
  for i = 0 : ∞
    E_Delay = (i + n_1) · m_1 · (L_M + 1) + i · j/2 + k · j + n_2 · m_2 · L_M
    if (m_1 > 0)
      for m = 1 : m_1
        E_Delay = E_Delay + (L_M + 1) · (m - 1) · L_M + (L_M - 1) · L_M/2;
      end
    end
    if (m_2 > 0)
      for m = 1 : m_2 - 1
        E_Delay = E_Delay + (L_M + 1) · m · L_M;
      end
      E_Delay = E_Delay + n_1 · (L_M - 1)/2;
    else
      E_Delay = E_Delay + n_1 · (n_1 + i - 1)/2;
    end
    T_Delay = T_Delay + P_{j,k} · p(i/j) · (E_Delay + j · (j - 1)/2);
  end
end

```

ALGORITHM 1: Algorithm for calculating the average number of waiting slots.

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