2010 3rd International Conference on Computer and Electrical Engineering (ICCEE 2010)
IPCSIT vol. 53 (2012) © (2012) IACSIT Press, Singapore
DOI: 10.7763/IPCSIT.2012.V53.No.1.78

A UWB MAC Protocol using Dynamic TH Code Assignment and Rate Control

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Abstract. Ultra wide band (UWB) has recently gained great interest. Designing a MAC protocol for UWB wireless network must take into account the physical layer characteristics. The TH-IR-UWB which uses short pulse as transmission signal and TH Code for spectrum spread has some special property that cause traditional MAC based on collision avoidance can not be used. In this paper, we propose a MAC for TH-IR-UWB called DTCARC-MAC. Taking into account the characteristics of UWB, DTCARC-MAC adopts a dynamic TH Code assigning schema and a rate controlling algorithm to accommodate simultaneous transmission, guarantees the link quality and enhance the throughput. The simulation results show that the proposed approach outperforms existing protocol for TH-IR-UWB.

Keywords: Medium access control; ultra wide band; rate controlling

1. Introduction

Ultra Wideband (UWB) [1] technology, which has a lot of benefits such as high band width, low cost, low power consumption, simple structure and high security has attracted a lot of attention lately from both industry and academy. It emits signal covers a large portion of bandwidth, and can be applied to short-distance high-speed multimedia transmission in indoor Wireless Personal Area Networks (WPAN) and long Communication distance, low communication rate wireless sensor networks (WSN).

Medium Access Control (MAC) problem is a core problem in wireless network. In recent years, there has been a lot of work on the issue of MAC design for UWB, such as [2], [3], [4]. Most of these works use TDMA schema to assign channel and Carrier Sense Multiple Access (CSMA) function to avoid collisions.

In this paper, we consider the MAC design problem for a wireless network using Time Hopping Impulse Radio UWB (TH-IR-UWB) as physical layer. A well-designed MAC protocol should take advantage of the characteristics of the physical layer technology to achieve low delay, high throughput and a good property of fairness. The TH-IR-UWB signal has very low level of power spectrum density, very broad bandwidth and no carrier, so receiver is difficult to detect the presence of the signal, which means that CSMA is not suitable to TH-IR-UWB. Moreover, in contrast with MAC protocols that rely on contention access which limits simultaneous transmissions, a MAC for TH-IR-UWB should be designed to accommodate multiple simultaneous transmissions. So the methods proposed in [2], [3], [4] are not the best choice of TH-IR-UWB. [5] proposes a MAC protocol according to the special feature of TH-IR-UWB, called UWB^2. The protocol is a multi-channel distributed CDMA MAC. It formulates the channel assignment problem as a TH code assignment problem. Each node is assigned to a fixed hopping code, and transmits information by the time hopping code, as a virtual “Link”. The Sending node and receiving node transfer handshake information through a common TH code. The sending node will send data using the TH code assigned, after the successful exchange of handshake information. [6] makes a analysis of the efficiency of the protocol.

Although UWB^2 is designed according to the feature of TH-IR-UWB, there are still some shortcomings. UWB^2 assigns a TH code to each node. When the network size increases, there are not enough TH codes for assigning. In

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addition, the UWB^2 protocol doesn't provide an effective method to suppress the Multi-User Interference (MUI). When the network load is high, the MUI is severe, which makes error rate of each link dramatically increase. For the above shortcomings of UWB^2, we propose a UWB MAC Protocol using Dynamic TH Code Assignment and Rate Control (DTCARC-MAC) on the basis of UWB^2. Using this MAC, more users can be supported using limited number of TH codes, and optimal throughput can be archived while ensuring the transmission error rate of each link.

The paper is organized as follows. In section II, the TH-IR-UWB signal model is introduced. The MAC description is then detailed in Section III. In section IV, simulation results are provided. Finally, a conclusion is given in section V.

2. TH-UWB-IR Signal Model

We assume that the signal model is as described in [1]. A transmitted signal using time hopping and Pulse Position Modulation (PPM) of the *k-th* user is given by:

$$s^{(k)}\left(t\right)=A\sum_{j=-\infty}^{\infty}w(t-jT_f-c_j^{(k)}T_c-\delta d_{\left\lfloor \frac{j}{N_s}\right\rfloor})$$

Where A is the amplitude and T_f denotes the frame time or pulse repetition time, and $w(t)$ is the monocycle pulse waveform. T_p denotes the width of the monocycle pulse, which has a typical value of 1ns. The time hopping shift of every monocycle is determined by the chip duration T_c and TH code $c_j^{(k)}$ with length N_S. TH sequences support multiple access communication. The values of $c_j^{(k)}$ are chosen from a finite set {0, 1, …, N_h-1}, δ denotes the PPM modulation shift value, and d means the information bit generated by the source.

At the receiver side, the received signal is the summation of N_u transmitted signal and the channel noise. It is given by:

$$r\left(t\right)=\sum_{k=1}^{N_u}A^{(k)}s^{(k)}(t-\tau^{(k)})+n(t)$$

Where $A^{(k)}$ and $\tau^{(k)}$ denote the attenuation and the delay of the signal transmitted by the *k-th* user, N_u is the user number, $n(t)$ is white noise.

If user 1 is concerned by the receiver, we can also rewrite the equation as:

$$r\left(t\right)=A^{(1)}s^{(1)}\left(t-\tau^{(1)}\right)+\sum_{k=2}^{N_u}A^{(k)}s^{(k)}(t-\tau^{(k)})+n(t)$$

The second term is the MUI in the network.

3. The Design of DTCARC-MAC

3.1 The main idea of DTCARC-MAC

The same as UWB^2, the DTCARC-MAC we proposed is multi-channel MAC. It takes advantage of the multiple access capabilities warranted by the TH codes for data transmission, and each hopping code can be regarded as a virtual channel. The main task of the protocol is to assign TH codes to the nodes which have data to transmit. To accomplish this goal, a public TH code is adopted as a common control channel for exchanging control information, and other TH codes are used for data channel.

Different from UWB^2, DTCARC-MAC is a centralized MAC. There is a central node in the network, with the name of Leader, and all the other nodes are called Terminals. The Leader coordinates all the transmission behaviors of the network, including TH Codes assignment, transmitter and receiver handshaking, etc. When a terminal N1 has some data to send to another Terminal N2, N1 should at first send a Request (RQT) packet to the Leader in the network using the public TH code. When the Leader receives the RQT packet, it assigns a TH code and a transmission rate to this request according to the current network condition. Then the Leader broadcasts a Response (RPS) packet which contains the sender, receiver, TH code and transmission rate information. After N1 and N2 received the RPS packet, a valid transmission can be set up using the specified TH code. The transmission will last for a pre-specified time named TimeSlot at the rate specified in the RPS packet. This process is illustrated in Figure 1.

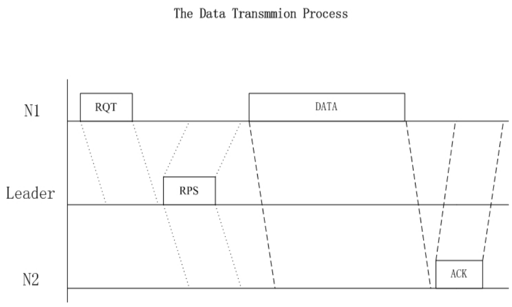

Figure 1.The process of a data packet transmission in DTCARC-MAC.

There are mainly two improvements in DTCARC-MAC compared with UWB^2. First, for the problem of TH codes assigning, UWB^2 pre-specified a TH code for each Terminal in the network. However, DTCARC-MAC does not assign TH codes to Terminals, instead it assigns TH Code to transmission request, and the Leader is responsible for managing all the available time-hopping codes. Second, DTCARC-MAC adopts a rate controlling schema. The Leader should assign a rate which is generated by a rate controlling algorithm for each request of transmission. This approach improves the network throughput and guarantees the transmission quality of each transmission.

3.2 TH code dynamically assignning schema

We use $S_{TH} = \{K_i, i=1,2,\ldots,N_{th}\}$ to denote the TH code set the protocol uses, and N_{th} is the number of all the TH codes, and K_i is a TH Code. To ensure the quality of transmission, the cross correlation between two TH Code K_i and K_j should not exceed a specified threshold λ. According to [7], if N_S and N_h are specified, we have equation: $N_{th} \le \frac{1}{N_s N_h}\left\lfloor \frac{N_s N_h}{N_s}\left\lfloor \frac{N_s N_h - 1}{N_s - 1} \cdots\cdots \left\lfloor \frac{N_s N_h - (\lambda-1)}{N_s - (\lambda-1)}\left\lfloor \frac{N_s N_h - \lambda}{N_s - \lambda} \right\rfloor\right\rfloor\right\rfloor\right\rfloor$ Therefore, the number of available time-hopping codes is limited. When the number of Terminals in the network is large, there are not enough TH codes to assign a TH code to each Terminal. In the DTCARC-MAC, a dynamic TH code assigning schema is adopted. A TH code is assigned to a transmission request but not a Terminal. When a Terminal has some data to transmit, it gets a TH code to transmit data by requesting to the Leader. The TH code can be reused to other request after a TimeSlot. By dynamically assigning the limited number of TH codes, DTCARC-MAC can support more Terminals than UWB^2 in [5].

3.3 The rate controlling algorithm

A well designed MAC protocol should guarantee that the Bit Error Rate (BER) of each transmission link is no more than a predefined threshold. When there are N_U current transmission links in the network, for the *i-th* link, the link transmission rate is R_i, the width of pulse is T_p, so the pulse rate of that link $G_i = R_i N_S$. As expressed in [5]. Under the reasonable hypothesis for asynchronous link that the pulse inter-arrival process follows a Poisson distribution, the probability that one pulse transmitted in link i doesn't collide with another pulse transmitted in link j can be expressed as:

$$P^{(j)}_{NonCollSingle} = e^{-2R_j N_s T_p}$$

The probability is calculated in the principles of ALOHA collision. So the probability that a pulse in link i collide with pulses transmitted by other links is:

$$\begin{aligned} P^{(i)}_{PulseCollision} &= 1 - \prod_{k=1,k\neq i}^{Nu} P^{(k)}_{NonCollSingle} \\ &= 1 - \prod_{k=1,k\neq i}^{Nu} e^{-2R_k N_s T_p} \\ &= 1 - e^{-2N_s T_p \sum_{k=1,k\neq i}^{Nu} R_k} \end{aligned}$$

Assuming that a pulse collision causes a random decision at the receiver side the pulse error probability can be expressed as:

$$P^{(i)}_{PulseError} = 0.5 P^{(i)}_{PulseCollision}$$

We assume a bit error happens when more than $N_S/2$ pulse errors occur, so BER in link i is:

$$P_{BitError}^{(i)} = \sum_{k=\left\lceil \frac{N_s}{2} \right\rceil}^{N_s} \binom{N_s}{k} \left(P_{PulseError}^{(i)}\right)^k (1-P_{PulseError}^{(i)})^{N_s-k}$$

If all the links have the same bit rate R, each link have the same collision probability:

$$P_{PulseCollision} = 1-e^{-2N_sT_p(N_u-1)R}$$

And the BER of each link is:

$$P_{BitError} = \sum_{k=\left\lceil \frac{N_s}{2} \right\rceil}^{N_s} \binom{N_s}{k} \left(0.5P_{PulseCollision}\right)^k (1-0.5P_{PulseCollision})^{N_s-k}$$

From the above formula, we can see that the summation of the transmission rate should be no more than a proper value in order to guarantee the BER of each link. So a rate control algorithm should be used. DTCARC-MAC adopts a rate control algorithm. The algorithm is used by the Leader. It splits the network time into some pieces so called TimeSlot, and in each TimeSlot, it record the transmission request received. The algorithm maintains a variable N_q which is the average number of request received in the last k TimeSlots. A lower border of BER is predefined, and the corresponding rate summation R_{Total} is pre-calculated too. When a request arrives, the Leader assigns a rate R_{Total} / N_q. This algorithm has two main procedures, a statistic updating procedure to update N_q, and a assigning procedure to assign a rate. The flow charts of the two procedures are described in Figure 2 and Figure 3.

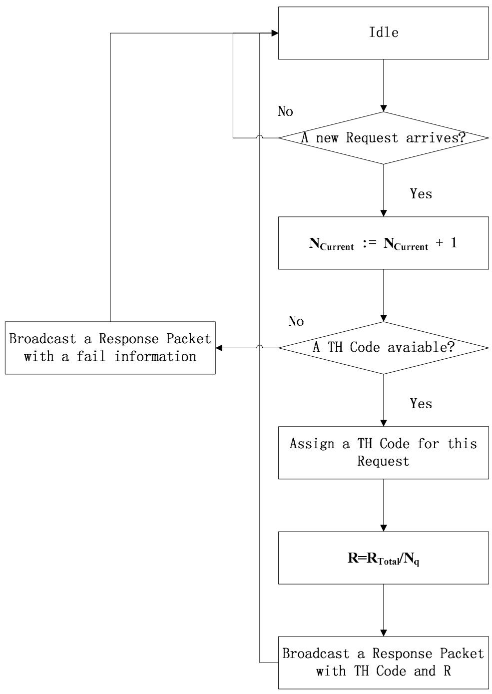

Figure 2. The flow chart of assigning procedure.

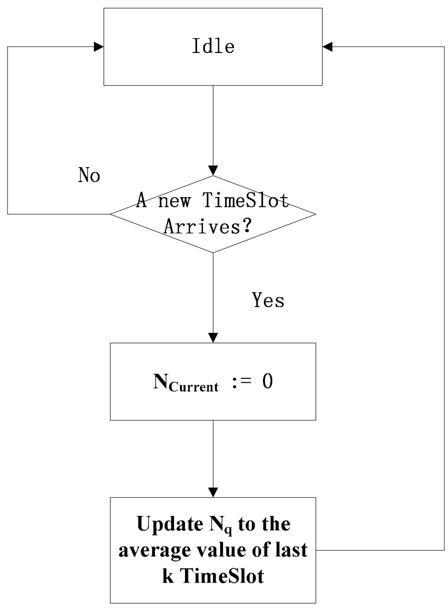

Figure 3. The flow chart of statistic updating procedure.

By rate control schema to requests, DTCARC-MAC guarantees that the error rate of each link will not exceed the preset limit, and because the effective control of error rate, DTCARC-MAC improves the effective throughput, compared with UWB^2. We demonstrate this in the simulation section below.

4. Simulation Results

We developed a simple simulator to evaluate the performance of our DTCARC-MAC. The simulator simulates the transmission and reception of pulses, and some details such as handshaking and synchronization are ignored. In the simulation scenario, there are 100 Terminals, and each Terminal is in the region of all other Terminals' transmission range. We set $N_S = 1, T_p = 1ns$, the bit generation rate of each Terminal is λ. We set a series of values to λ, and simulated both under DTCARC-MAC and UWB^2 to compare the performance.

Two performance indicators are considered. The same as in [5], the throughput defined as the ratio between successfully received bits and transmitted bits, and Bit Error Probability based on the analytical model derived in Section III.

The measured values for BER are presented in Figure 4, we can see that the BER in DTCARC-MAC performs are better than in UWB^2, especially when the network load is high. That is because the adopting of rate control schema.

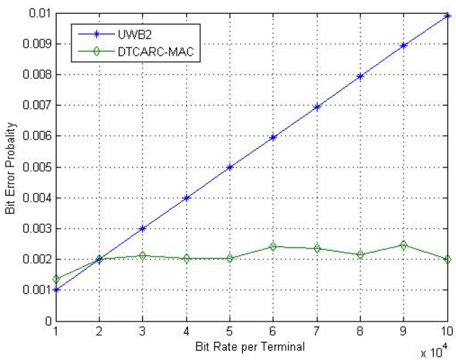

Figure 4. The Bit Error Probality results.

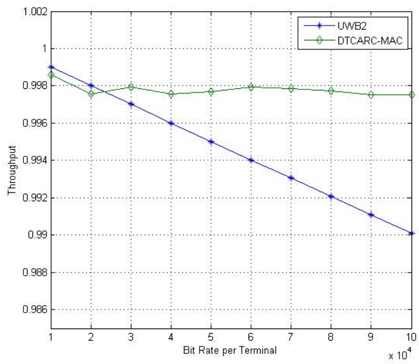

Figure 5. The Throughput results.

The measured throughput are presented in Figure 5, we can see that DTCARC-MAC beats UWB^2 thanks to the rate controlling algorithm.

5. Conclusion

In this paper, we propose a MAC protocol for TH-IR-UWB. The proposed protocol takes into account the special properties of TH-IR-UWB such as unable to be applied to CSMA, large synchronization overhead and the ability of simultaneous transmitting. Based on UWB^2, the proposed protocol mainly makes two improvements. It adopts a dynamic TH code assigning schema to enlarge the number of nodes supported and a rate controlling schema to increase the effective throughput of the network while guarantee the transmission quality. According to simulation results, our approach outperforms UWB^2 in the respect of BER and effective network throughput.

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