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An Improved High Throughput and Low Delay Access Protocol for Terahertz Wireless Personal Area Networks

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Abstract. Terahertz (THz) wireless personal area networks (T-WPANs) operate in the terahertz band, which has greater signal attenuation especially when the air is rich in water molecules, so it's essential to consider the signal attenuation characteristics of the wireless link in terahertz wireless communication. In this paper, we focus on the poor link condition in T-WPANs, and a improved high throughput and low delay MAC protocol (IHTLD-MAC) for T-WPANs is proposed. By the on-demand retransmission mechanism based on verification, reserved time slots mechanism based on channel condition and the dynamic acknowledgement mechanism adaptively, IHTLD-MAC can allocate the slots resource reasonably, improve the network throughput and reduce the data latency. The simulation results show that IHTLD-MAC has better network performance compared with the existing IEEE 802.15.3c and the ES-MAC in bad link condition.

Keywords: link condition, MAC protocol, terahertz, wireless personal area networks

1 Introduction

Wireless personal area network [1] (WPAN) is a self-organizing network for high-speed data switching between multiple members at close range, which do not require infrastructure and have broad application prospects in the new era. However, the traditional WPAN can only support a maximum data rate of 5.775 Gbps, which has gradually difficulty to meet the demand for high data rate, so new solutions have been sought for. Recently, great changes have taken place in the way of producing, sharing and consuming information and new applications with higher bandwidth requirements have been proceeding. On the one hand, it results in a sharp increase in wireless data traffic; on the other hand, it also causes growing demand for higher data rate in wireless communication. Some promising wireless applications require the data rate up to several 10 Gbps [2]. As the picture shows in Fig. 1, according Edholm's law, data rate of the wireless communication system will be close to 100 Gbps around 2020 [3]. In existing network solutions, such as wireless personal area networks (WPANs), wireless local area networks (WLANs), wireless metropolitan area networks (MANs), wireless sensor networks (WSNs), data transmission rate for more than 10 Gbps can hardly be supported. In order to meet the demand for higher data rate of wireless communications, communication system using terahertz band as carrier wave is the significant choice [3].

On the spectrum, terahertz wave [4-5] is a kind of electromagnetic wave which locates between millimeter wave and infrared wave, as shown in Fig. 2. The wavelength of terahertz situates in the range of 0.03 mm-3 mm, the corresponding frequency 0.1 THz-10 THz. It lies within the transition zone from macro classical theory to microscopic quantum theory and it is the last one not having been fully acquainted with yet. Terahertz waves have the following characteristics:

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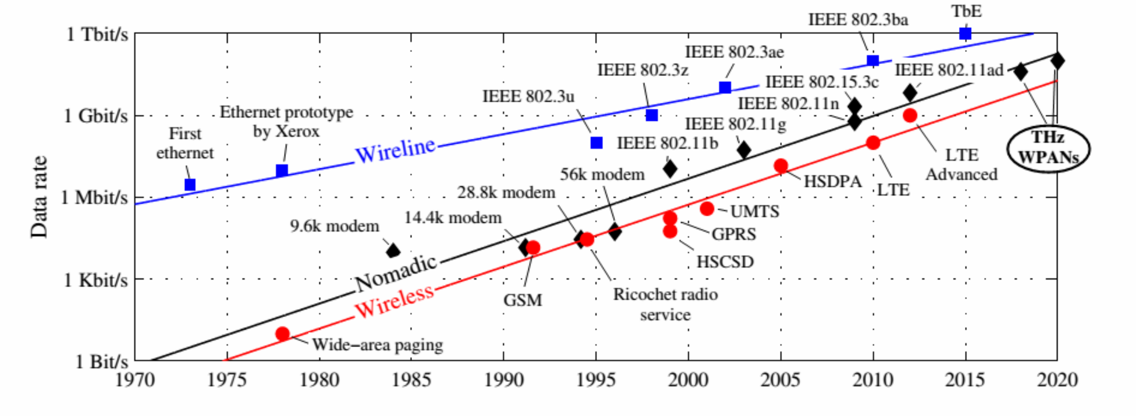

Fig. 1. Growth trend of data rate

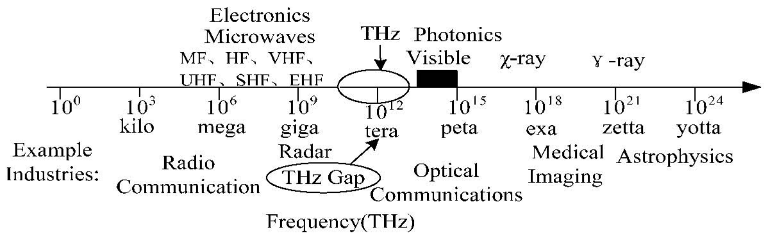

Fig. 2. Terahertz spectrum

(1) Short wavelength [6], 0.03 mm-3 mm. Compared to other systems, because of its much smaller antenna size, it can be done more economically;

(2) A large spectral bandwidth [7], 0.1 THz-10 THz. As for wireless transmission rate, it is usually up to several 10 Gbps [3];

(3) Good stability. It can still work well in bad conditions [6].

(4) Good privacy and anti-jamming capability [6]. Consider using it in more complex network condition.

(5) Large attenuation [8]. It has greater signal attenuation especially when the air is rich in water molecules, as shown in Fig. 3.

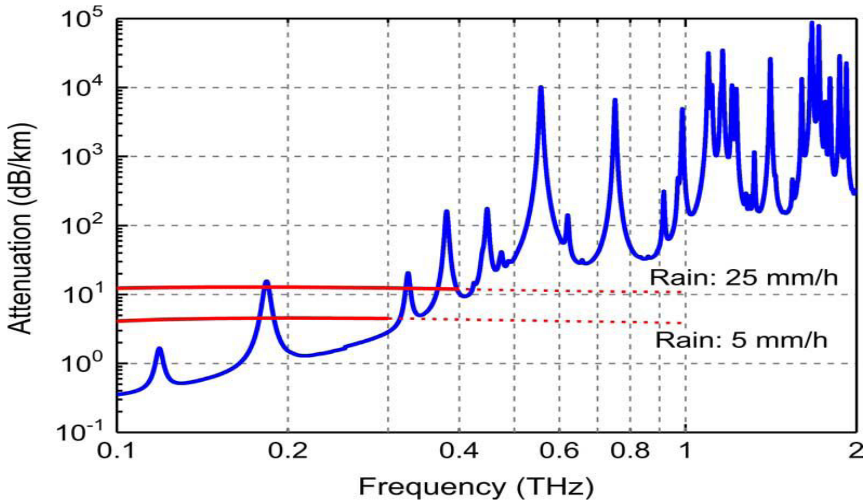

Fig. 3. Terahertz atmospheric attenuation

Before the 1990s, due to the lack of effective THz wave source and appropriate detection technique [9], it threw out great challenges for terahertz application. In recent years, the rapid development of laser technology to generate THz waves provides a stable and reliable laser light source. Base on above, the terahertz wave detection technology and its application has also been widely developed.

Terahertz technology can be widely used in many areas, such as radar, remote sensing, homeland security and counter-terrorism, detection of atmospheric environment, extraction of real-time biological information, high security data transmission, medical diagnosis, and so on [9]. Thus, terahertz technology has an irreplaceable role for national security and the national economy. Its use and development fills the gap of bandwidth over 300 GHz.

Terahertz band [5] (0.1-10 THz) has great unused bandwidth with capable of carrying data at gigabit level. It may be the first choice for the future wireless communication. T-WPANs is a new network which works in the terahertz frequency and can support data rate of 10-50 Gbps. It presents a great challenge for MAC layer. MAC protocols with more efficient channel resources management are needed to achieve the high-speed wireless communications.

Most studies of existing terahertz WPAN MAC protocols [10-13] are based on IEEE 802.15.3c channel access section, and taking the environmental characteristics into account at the same time. Priebe [10] has proposed the MAC layer concepts for terahertz communications. By comparing and analyzing the MAC layer functions that have to be achieved in several different terahertz use-cases, he pointed out that different MAC protocols should be directed to different THz use-cases. He has also recommended that T-WPANs MAC protocol should adopt IEEE 802.15.3c as a reference to modify and form a new agreement. Peng [11] and his team have studied directional search for indoor THz communications. High path loss in terahertz frequencies makes it much difficult to search directionally, while the antenna calibration method in IEEE 802.15.3c is no longer suitable for the terahertz band, so they put forward a new method, a fast and practical beam searching concept for the AoA and AoD estimation in two steps. In the first step, a preliminary estimation is carried out at a lower frequency via exhaustive scanning. After that, the precise angle is estimated at the actual frequency for the data transmission. Jornet et al. [12] proposed a terahertz electromagnetic nano-network MAC protocol. By taking advantage of the characteristics of the physical layer burst communication, data can be sent directly without waiting. Low-weight-coding and repetition-coding are introduced to reduce the error rate, but the use of these coding schemes will greatly reduce the coding efficiency. In their following researches [13], a link-layer synchronization MAC protocol (LLS-MAC) was proposed, which used the way of receiver-initiated handshake to guarantee link-layer synchronization between transmitter and receiver. In addition, it incorporated a sliding window flow control mechanism to maximizes the channel utilization. The simulation results show that it can maximize the packet delivery probability successfully but not compromising throughput at all in THz-band communication networks. Cao et al. [14] described a high-throughput low-delay MAC protocol for terahertz ultrahigh data-rate wireless networks. To address the problem, not updating the time slot requests in time, a new superframe structure was proposed. It reduced the data access delay largely with a new superframe structure, from which nodes in piconet could get time slot allocation immediately. The network throughput was also improved with the help of updating time slot requests number. However, a new superframe structure proposed in this paper can reduce data latency effectively. As can be seen from above, research on T-WPANs MAC protocol has made some progress, but they pay no attention to poor network condition with unstable wireless link when designing the mechanism, which results in a decline in network throughput. To solve this problem, we propose an improved high throughput and low delay MAC protocol (IHTLD-MAC), followed by a simulation.

The rest of paper is organized as follows. In section 2, the network model is introduced briefly, followed by research progress having been made and some existing problems. In section 3, IHTLD-MAC is proposed and explained. In addition, experimental results are presented in section 4. Finally, the conclusions are drawn in section 5.

2 Network Model and Problem Description

2.1 Network Model

T-WPANs is a kind of Ad hoc network which uses terahertz frequency band as a carrier wave and the data rate can reach up to the Gbps level. T-WPANs are usually composed of several devices (DEVs) and a piconet coordinator (PNC). DEV is the basic unit of the network communication, while the PNC is a special DEV with more functions, and is responsible for channel access in network. PNC provides time synchronization information to DEVs and takes charge of the scheduling, access control, as shown in Fig. 4. Through beacon frames, PNC provides channel access information, the channel slots assignment information and synchronization information for all other DEVs. Data can be transferred between any two nodes (PNC or DEVs) and the maximum data rate can reach up to 10 Gbps or even more in this network.

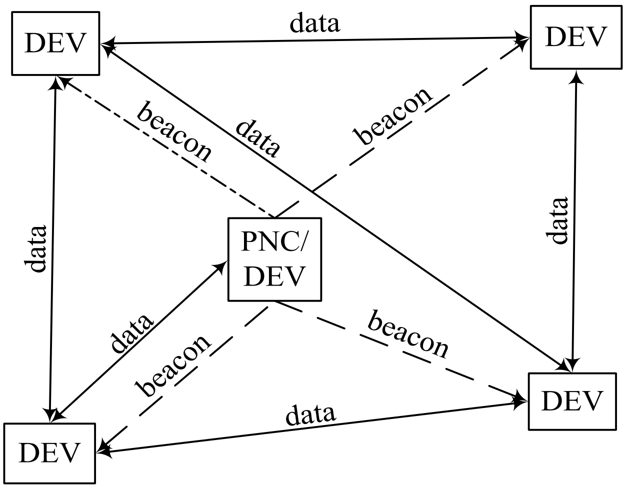

Fig. 4. Terahertz wireless personal area networks

The channel time in T-WPANs is divided into multiple superframes, and each superframe consists of three parts: Beacon Period (BP), Channel Time Allocation Period (CTAP) and Channel Access Period (CAP). As Fig. 5 shows, CSMA/CA and TDMA hybrid access mode is taken in each period. PNC sends omnidirectional beacon frame during BP in each superframe, which includes network synchronization information, slot allocation information and some other control information. After receiving the beacon frame, DEVs will synchronize themselves based on synchronization information and obtain CTAP slot allocation information about themselves. CTAP is formed by a series of channel time allocations (CTAs), and DEVs access channel in TDMA mode, each DEV transmits data in its own slot. CSMA/CA is used to compete for channel in CAP period. The DEV which wants to transmit data need to send a Channel Time Request Command to PNC, then PNC broadcast slot assignment information in the next beacon frame according to request frame received.

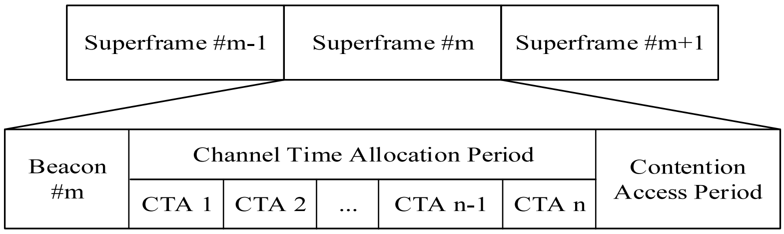

Fig. 5. Superframe structure for T-WPANs

2.2 The Classification of Terahertz Access Protocol and Its Research Progress

Although complete terahertz MAC protocol standard is not yet available, according to terahertz interest group's advice, terahertz MAC layer should depend on the utility model and different application should adopt different MAC solutions [10]. The terahertz MAC protocol is divided into two broad categories: 1) terahertz WPAN/WLAN MAC protocol; 2) point-to-point wireless MAC protocol. Among the second class, it can be divided further into two parts, MAC protocol between fixed point and non-fixed point, MAC protocol between fixed point and fixed point. The current research on T-WPANs MAC protocol mainly focuses on the study of the original IEEE 802.15.3c MAC protocol optimization.

2.3 Problem Description

In this section, problems are described from three aspects.

(1) Aggregation may be performed for high-speed data/video transmission or low-latency bidirectional date transmission. In IEEE 802.15.3c, standard aggregation is one of two aggregation methods defined. Fig. 6 illustrates the aggregation process. A subheader is created and configured for each subframe to contain the necessary information that helps the target DEV to retrieve the original data. For example, subheader1 (Sh#1)will be filled with important fields for subframe#1 to be recognized by target DEV. Fig. 7 illustrates the deaggregation process. We can see that the longer the frame, the greater the probability of error. In IEEE 802.15.3c, when error occurs within MAC subheaders (containing the length of each subframe section and other information) of aggregated frame, the length of each MSDU cannot be obtained so the whole aggregated frame should be retransmitted. If part of MAC subheaders and its corresponding subframes is correct, they will have no need to be retransmitted. But in existing mechanism, all of them will be retransmitted as long as error occurs within MAC subheaders. From the above analysis, we can see that it will result in larger redundancy and data delay in poor link condition.

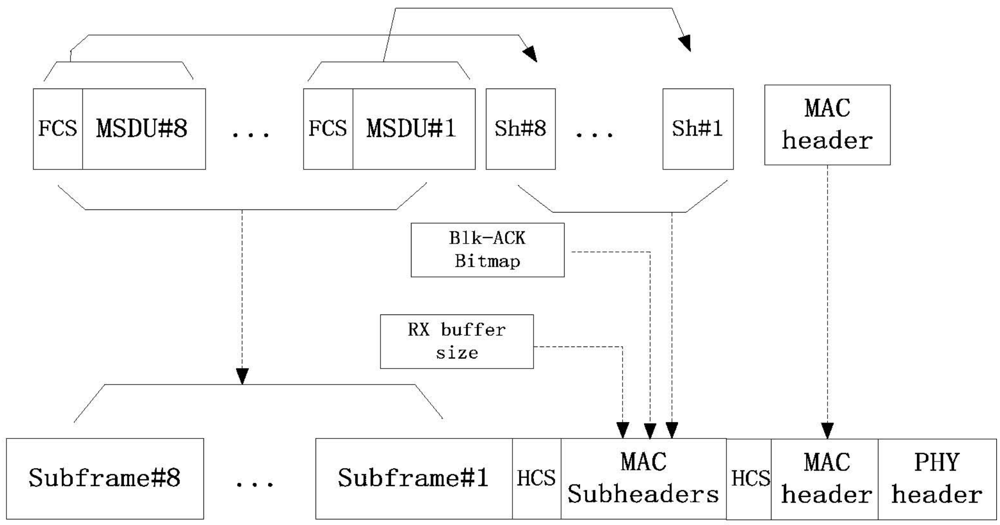

Fig. 6. Aggregation at originating DEV

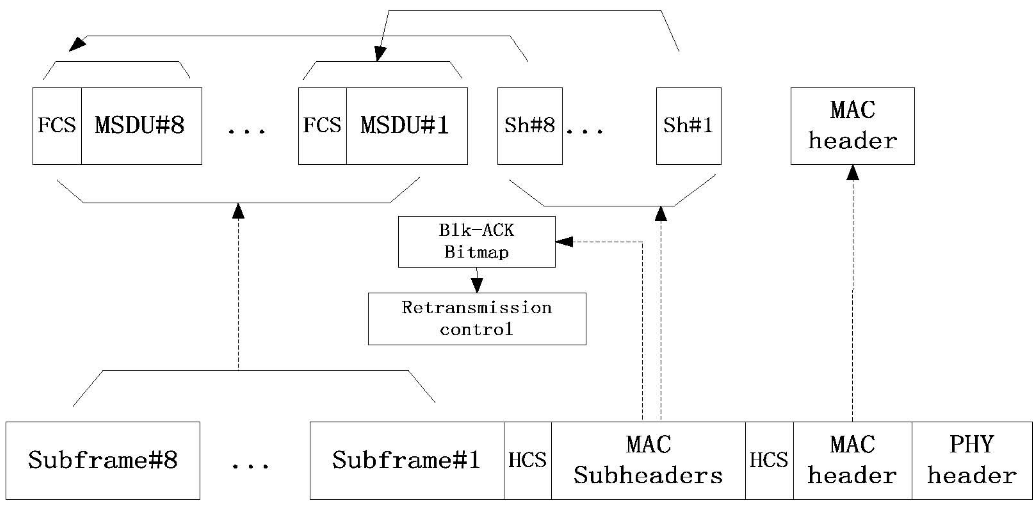

Fig. 7. Deaggregation at target DEV

(2) In IEEE 802.15.3c, the Channel Time Request Command may be used to request, modify, or terminate CTAs corresponding with either isochronous streams or asynchronous data traffic. In

conventional channel time request, DEV determines the time slots planning to apply for according to the amount of data within the cache. But it ignores the data retransmission when error occurs. Data retransmission will still occupy the time slots applying for last time. Due to insufficient allocated resources in this superframe, some data transmission has to be deferred to next superframe. Thus the waiting time of data is increased and the network throughput drops.

(3) In order to reduce network overhead and enhance network performance, aggregation mechanism is proposed in IEEE 802.15.3c. However, due to the poor channel condition in T-WPANs, if the mechanism is applied to terahertz frequencies directly without change, subframes in aggregated frame will go wrong and can't be retransmitted in time. It will waste more channel resources, increase the data transmission delay and affect network throughput performance seriously.

3 IHTLD-MAC

3.1 The On-demand Retransmission Mechanism Based on Verification

To decrease the redundancy overhead, we come up with the on-demand retransmission mechanism based on verification.

First, originating DEV conducts a special 8 bit cyclic redundancy check of data for the first four subheaders (20 bytes) within MAC subheaders of aggregation frame. Calibration results are stored in the 8 reserved bits (each data frame subheader has 1 reserved bits, 8 data frames total 8 bits) of aggregated frame MAC subheaders.

Then, after target DEV receives aggregated frame, checking whether the MAC subheaders make a mistake.

Next, if an error occurs, then take out the first four subheaders and conduct cyclic redundancy verification, compare and verify the results with reserved bits in MAC subheaders of aggregation frame. If equal, indicate that the first four subheads of data frames are correct. Checking if the corresponding data frame is correct.

Finally, if the correct data frame exists, the target DEV will inform the originating DEV that some frames having been received correctly should be retransmitted again by Imm-ACK. If an error has occurred in 8 bits parity, the target DEV should inform originating DEV of retransmitting the entire aggregated frame.

3.2 The Reserved Slots Mechanism Based on Channel Condition

To solve the problem that the data retransmissions will occupy the time slots, leading to some data to be deferred to next superframe, the reserved slots mechanism based on channel condition is proposed. The reserved slots mechanism based on channel condition are as follows.

The main parameters of the the reserved slots mechanism are shown in Table 1.

Table 1. Important symbol

Notations	Description
P_k	Channel error rate
L_A	The size of ACK frame
L	The size of data frame
P_s	The transmission success rate of data frame
N	The maximum number of retransmission
S_i	The amount of initial slots request
S_u	The amount of updated slot request

If having data to send in cache, DEV will prepare Channel Time Request Command in CAP. Firstly, the DEV sets S_i according to the amount of data in cache. Then, the worst situation that data is received successfully or destroyed after N times retransmission is also need to be considered. Next, calculate the average error number among Si based on channel condition which is represented by Pk. Finally, according to the time slot reserved for the retransmission of data, it can avoid some data transmitting in next superframe, which decreases the data transmission delay.

According to the above mechanism, the S_u can be calculated as (1):

$$S_u = S_i + S_i * (1 - P_s) * (\sum_{n=0}^{N} P_s (1 - \mathrm{P}_s)^n * n) . \quad \textbf{(1)}$$

P_s can be obtained from P_k, as (2) shows:

$$S_u = S_i + S_i * (1 - P_s) * (\sum_{n=0}^{N} P_s (1 - \mathrm{P}_s)^n * n) . \quad \textbf{(2)}$$

Actually, the channel error rate (CER) is more difficult to be obtained in the network, and its main usage is to calculate the frame error rate (FER) F_e. Therefore, we use F_e replace CER, such as formula (3). F_e can be obtained dynamically by the number of data frames having been transmitted and the number of data frames having been received correctly at the target DEV.

$$S_u = S_i + S_i * F_\mathrm{e} * (\sum_{i=0}^{N} (1 - F_e) * F_e^{\,i} * i) . \quad \textbf{(3)}$$

This mechanism takes a full consideration of the poor channel condition in T-WPANs. By the reserved slots mechanism based on channel condition, it can reduce data latency and improve network throughput effectively.

3.3 Dynamic Acknowledgement Mechanism Adaptively

Aggregation mechanism is a method to aggregate several frames into an aggregated frame, and adopt block acknowledgment frame (Blk-ACK) to respond. The method can reduce the MAC header overhead and improve network throughput. However, it is not adapted to the situation with poor channel condition. Once a subframe goes wrong, the subsequent subframe cannot be extracted correctly, which results in a sharp decline in network throughput. To solve this problem, a dynamic acknowledgement mechanism adaptively is proposed based on channel condition, the related principles are as follows.

Network throughput model with immediate acknowledgment (Imm-ACK) policy (no aggregation). In reference [15] and [16], the authors proposed an analyzing model for network throughput. Based on this, we make some improvements and propose a network throughput analysis model for T-WPANs MAC. P_k represents the channel error rate, l_{ack} is the size of Imm-ACK frame, $P_e(l)$ represents the error rate of a frame whose length is l bit. $P_e(l)$ can be calculated as formula (4), and then the transmission success rate of a data frame with length l can be calculated as (5):

$$P_e(l) = 1 - (1 - P_k)^l \quad \textbf{(4)}$$

$$P_{succ}(l) = (1 - P_{e,\mathrm{o}}(l_{ack})) * (1 - P_{e,data}(l)) = (1 - P_k)^{(l_{ack}+l)} \quad \textbf{(5)}$$

Provided that the average survival time of a data frame within network is τ . The average survival time of a data frame within network contains two situations, the time of successful data frame transmission and the time of failing data frame transmission. Successful transmission of data includes no retransmission and retransmission for many times but successful finally. Failure transmission of data means after the maximum N times retransmission, the target DEV still has not received the data correctly. So τ can be calculated as formula (6):

$$\tau = \sum_{i=0}^{N} P_{succ}(l) * (1 - P_{succ}(l))^i (i * t_{fail} + t_{succ}) + (N + 1) * (1 - P_{succ}(l))^{(N+1)} * t_{fail} \quad \textbf{(6)}$$

t_{fail} is the time of data frame transmission failure while t_{succ} is the time of data frame transmission success, and both of them can be calculated as formula (7) and (8) separately:

$$t_{fail} = t_p + \frac{l_h}{R_l} + \frac{l}{R_h} + t_{RIFS} \quad \textbf{(7)}$$

$$t_{succ} = t_p + \frac{l_h + l_{ack}}{R_l} + \frac{l}{R_h} + 2t_{SIFS} \quad \textbf{(8)}$$

t_p represents the time of the preamble. R_h denotes the transmission rate of data frame. R_l shows the transmission rate of MAC header and ACK frame (R_l is less than R_h). t_{SIFS} is the short inter-frame interval and t_{RIFS} is the retransmission inter-frame interval. Provided that ρ is the ratio which CTAP period accounts for the whole superframe, the network throughput for the data frame with length l in Imm-ACK policy can be calculated as formula (9):

$$C_{Imm} = \frac{\rho * l}{\tau} * (1 - (1 - P_{succ}(l))^{(N+1)}) \quad \textbf{(9)}$$

Network throughput model with Blk-ACK policy (adopt aggregation). P_k represents the error rate. l_{sub} is the length of subframe in bit. l_h represents the length of MAC header in aggregated frame. N_{blk} denotes the number of subframe in a aggregated frame. l_{sub_h} reveals the length of subframe header, meanwhile l_{blk_ack} for the length of Blk_ACK frame. From above, we can see that the transmission success rate of a subframe with length l_{sub} can be calculated as formula (10):

$$\begin{aligned} P_{suc}(l_{sub}) &= (1 - P_{e,o}(l_h + N_{blk} * l_{sub\_h} + l_{blk\_ack})) * (1 - P_{e,data}(l_{sub})) \\ &= (1 - P_k)^{(l_h + N_{blk} * l_{sub\_h} + l_{blk\_ack} + l_{sub})} \end{aligned} \quad \textbf{(10)}$$

The survival time of a subframe in the network τ' can be calculated as (11):

$$\tau' = \sum_{i=0}^{N} P_{succ}(l_{sub}) * (1 - P_{succ}(l_{sub}))^i (i * t'_{fail} + t'_{succ}) + (N+1) * (1 - P_{succ}(l_{sub}))^{(N+1)} * t'_{fail} \quad \textbf{(11)}$$

t'_{succ} is the time of subframe transmission failure while t'_{fail} is the time of subframe transmission success, which can be calculated as (12) and (13) separately:

$$t'_{succ} = t_p + \frac{l_h + N_{blk} * l_{sub\_h} + l_{blk\_ack}}{R_l} + \frac{N_{blk} * l_{sub}}{R_h} + 2t_{SIFS} \quad \textbf{(12)}$$

$$t'_{fail} = t_p + \frac{l_h + N_{blk} * l_{sub\_h}}{R_l} + \frac{N_{blk} * l_{sub}}{R_h} + t_{RIFS} \quad \textbf{(13)}$$

As can be see from (12) and (13), the survival time of a subframe mainly depends on the size of entire aggregated frame. The greater the length of the aggregated frame, the longer the time of the success or failure transmission. Based above, the network throughput for the subframe with length l_{sub} in Blk-ACK policy can be calculated as (14):

$$C_{agg} = \frac{\rho * N_{blk} * l_{sub}}{\tau'} * (1 - (1 - P_{succ}(l_{sub}))^{(N+1)})^{N_{blk}} \quad \textbf{(14)}$$

Because it is more difficult to obtain the bit error rate in wireless networks, so we use frame error rate F_e instead. The originating DEV calculates the proportion that data frame having been sent successfully accounts for the whole transmitted data frame in current CTA according to the received ACK frames. F_e can be obtained by one minus the proportion. Using F_e replaces P_k, we can get formula (15) and (16) from (9) and (14):

$$C_{Imm} = \frac{\rho * l}{\tau} * (1 - F_e^{(N+1)}) \quad \textbf{(15)}$$

$$C_{agg} = \frac{\rho * N_{blk} * l_{sub}}{\tau'} * (1 - F_e^{(N+1)})^{N_{blk}} \quad \textbf{(16)}$$

To facilitate the analysis, assuming that the network adopts aggregation mechanism in the initial phase, every aggregated frame has the same number of subframe and each subframe has the same length. The operations of the dynamic acknowledgement mechanism adaptively are as follows.

If there are some data that need sending, the originating DEV will calculate the network throughput according to the formula (15) and (16) based on current F_e. If the calculated C_{agg} is larger than C_{Imm}, then adopt aggregation mechanism with Blk-ACK to transmit data, else Imm-ACK policy without aggregation mechanism. The source DEV should indicate the ACK policy in the ACK mode field to inform the target DEV. The F_e will be updated in current CTA by originating DEV based on the number of received ACK frames.

By determine whether to use the aggregation mechanism based on the current network channel condition, this mechanism can avoid the negative impact of aggregation mechanism with poor channel condition, and maximize the network throughput.

4 Simulation Analysis

We conduct a series of simulation experiments with OPNET 14.5 to evaluate the performance of IHTLD-MAC. Two relevant algorithms, IEEE 802.15.3c and ES-MAC are selected for comparison.

4.1 Simulation Parameters Specifications

The main parameters of the simulation are shown in Table 2.

Table 2. Simulation parameters

Simulation parameters	value
scene(m2)	20×20
communication radius (m)	10
number of DEV	11
Carrier frequency (GHz)	340
FER(%)	2,4,6,8,10
Packet generation interval(s)	0.00008
packet size(bytes)	8192
Physical layer rate(Gbps)	10
Cache Size(MB)	10
Simulation time(s)	50

4.2 Simulation Results and Analysis

The simulation results and analysis are presented below. Observed metric we take include network throughput, average delay, access success rate and buffer overflow rate.

Network Throughput. Network throughput is the average bits received successfully by destination during per unit time. As shown in Fig. 8, network throughput has decreased in all three types of protocols with the network frame error rate increasing. The throughput of IHTLD-MAC is higher than others, which mainly results in the adoption of dynamic acknowledgement mechanism adaptively. Meanwhile, the reversed slots mechanism based on channel condition making full use of the channel resources improves network throughput as well.

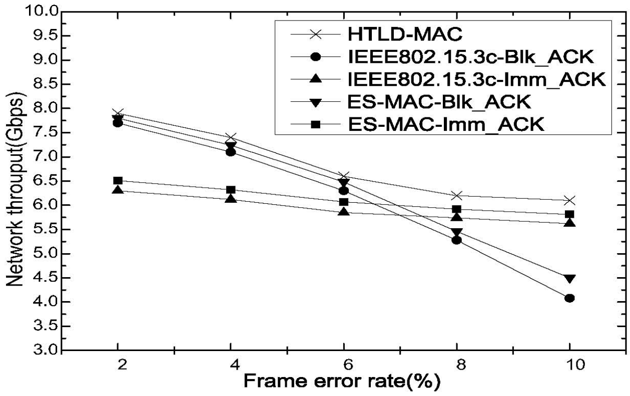

Fig. 8. Network throughput

Average delay. The average delay is the average consuming time of data frames from being generating to being received successfully. As can be seen from Fig. 9, IHTLD-MAC has a smaller frame average delay than others, there are mainly two reasons: (1) The reserved slots mechanism can effectively avoid the situation that the retransmission data occupies the time slots which results in part of the data being transmitted in the next superframe; (2) Dynamic acknowledgement mechanism adaptively has combined the advantage of Blk-ACK and Imm-ACK, bringing faster data forwarding.

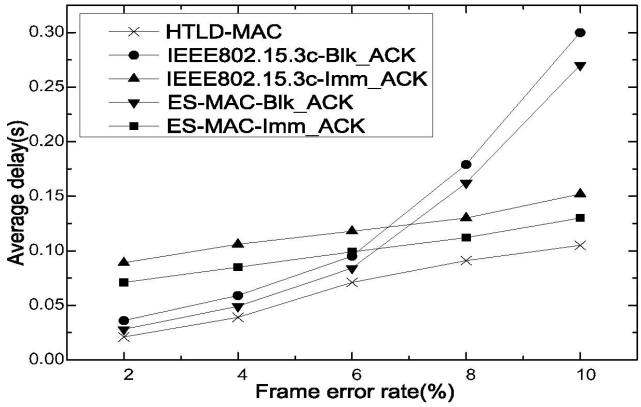

Fig. 9. Average delay

Access success rate. Access success rate is the proportion that the amount of data having been transmitted accounts for the amount of received data in MAC layer, which reflects the efficiency of MAC protocol. Fig. 10 shows that the IHTLD-MAC has better access success rate than others, there are two reasons to account for that: (1) The reserved slots resources enable all the data sent in the current superframe, reducing the backlog of data in the cache; (2) The dynamic ACK mechanism adaptively selects better acknowledgement mechanism to reduce network overhead and improve the access success rate.

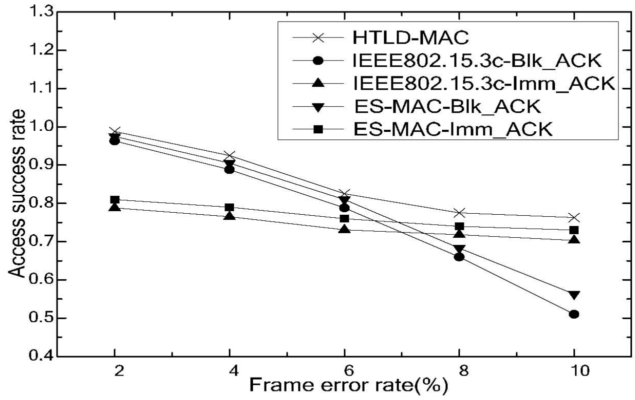

Fig. 10. Access success rate

Buffer overflow rate. Buffer overflow rate is the ratio of the amount of overflow data accounts for the total amount of data. As can be seen from the Fig. 11, IHTLD-MAC has the lowest buffer overflow rate, there are mainly two reasons: (1) Adaptive dynamic acknowledgement mechanism selects suitable network conditions to improve data transfer efficiency and reduce the backlog of data in cache; (2) The reversed slots resource speeds up data forwarding, and reduces buffer overflow.

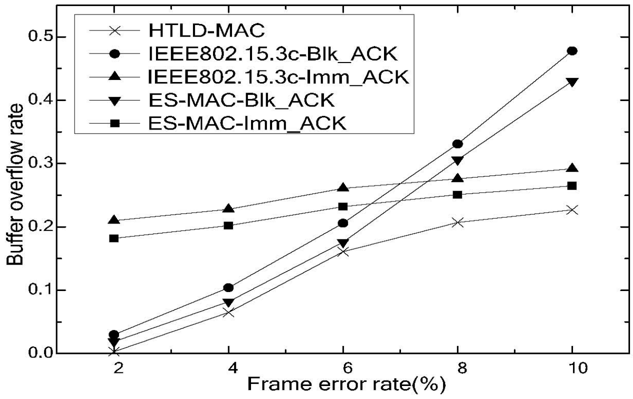

Fig. 11. Buffer overflow rate

5 Conclusion

Aiming at the poor T-WPANs condition and unstable wireless link, an improved high throughput and low delay MAC protocol for T-WPANs is proposed. By the on-demand retransmission mechanism based on verification, the reversed slots mechanism based on channel condition and dynamic acknowledgement mechanism adaptively, IHTLD-MAC has solved the three problems: (1) It decreases the redundancy overhead when in poor channel condition. (2) Even though the retransmission data occupies allocated slots, it makes no difference to source data planning to send. That is to say, source data planning to send has no need to send in next superframe. (3) Network throughput declines sharply with aggregation mechanism when the network condition is very poor. The simulation results show that IHTLD-MAC has superior network performance compared with IEEE 802.15.3c and ES-MAC, and is more suitable for T-WPANs. In the future, we will study slots allocation algorithm for T-WPANs based on IHTLD-MAC to promote the development of T-WPANs MAC protocol.

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