UWB-based Receiver Initiated MAC Protocol with Packet Aggregation and Selective Retransmission

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Abstract—**The media access control(MAC) protocol plays an important role in UWB-based wireless multimedia sensor networks (WMSNs). The problems of long acquisition time, large overhead and high collision probability have been addressed most when designing such MAC protocols. To reduce long acquisition time and large overhead, and to support more concurrent transmissions, we proposed a UWB-based MAC protocol for wireless multimedia networks named as UWB-based Receiver initiated MAC protocol with Packet aggregation and Selective retransmission (URMPS). The receiver initiated request, packet aggregation and selective retransmission are used to reduce synchronization acquisition time and overhead. The combination of mutually exclusive area and time-hopping(TH) code is to mitigate the interference caused by concurrent transmissions of multiple nodes. The simulation results run over NS-2 show that URMPS protocol performs better in terms of network throughput and delay compared to S-MAC. By incorporating all of above technologies into URMPS, the objective of improving the network throughput and reducing the network delay is achieved. Meanwhile, it can be used in the networks with moderate data traffic.**

Index Terms— **MAC protocols, UWB, wireless multimedia sensor networks**

I. Introduction

Wireless multimedia sensor networks (WMSNs) increasingly obtain the concern and attention of the academic community because of its rich media sensing functions. However, compared to traditional wireless sensor networks, wireless multimedia sensor networks are more stringent in terms of bandwidth, energy consumption and QoS requirements[2][3]. They require the support of physical layers with wide bandwidth. In recent years, emerging ultra-wideband technology has characteristics of wide bandwidth and low transmission power[4][5][5][7][8], so it is very promising to employ UWB as the physical layer of WMSNs.

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The unique characteristics of UWB brings opportunities as well as new challenges to the MAC layer design[5]. First of all, the transmitting power is a strict constraint in UWB networks. The ultra-low transmission power makes the data very susceptible to external noise interference in the channel, which causes failure of the data receiving at the receiver. Secondly, the transmission rate is high. For such a high data transmission rate, the time overhead introduced by the MAC protocol may waste a lot of resources, which greatly lead to terrible network performance. So the time overhead should be controlled in the first priority when designing a MAC protocol in UWB networks. Thirdly, UWB networks have long acquisition time. In UWB networks, in order to obtain the synchronization between the receiver and the sender, the sender sends a preamble which lasts tens of μs to tens of ms before the start of communication. The long synchronization time overhead may greatly degrade the efficiency of the UWB systems.

Conventional wireless network MAC protocols mainly exploit CSMA/CA used in the IEEE802.11 [7][9][10][11][12][13]. It is not appropriate, however, to directly use CSMA / CA in the UWB-based networks because of non-carrier characteristics in UWB networks [5][5]. Recent studies show that taking the unique characteristics of UWB physical layer into consideration can effectively improve the performance of the MAC protocols. In this paper, a new UWB-based MAC protocol which is named as UWB-based receiver initiated MAC protocol with packet aggregation and selective retransmission is proposed. In this protocol, receiver initiated communication request, packet aggregation, selective retransmission, mutually exclusive area and TH code mechanisms are used. The receiver initiated communication request is designed to reduce channel capturing time. Packet aggregation mechanism can further reduce channel capturing time and overhead of controlling frame interactions, and selective retransmission is aimed to avoid energy waste to transmit those frames correctly received. Adopting the combination of mutually exclusive area and TH code can reduce the probability of frame collision and control concurrent transmission interference effectively, respectively. Through the above mechanisms, the objective of improving network throughput and reducing network latency is achieved. So it can provide a good support for the transmission of multimedia information.

The rest of the paper is organized as follows: Related work is introduced in section II. The key component of the designed protocol is introduced in section III. The simulation results of the protocol over the NS-2 platform are given in Section IV by comparing to the simulation results of S-MAC over UWB physical layer. At last, the conclusion is given in section V.

II. Related Work

Researchers have proposed variety of MAC protocols to support networks adopting UWB technology as the physical layer. These protocols can be categorized as centralized MAC protocols and distributed MAC protocols according to whether there is a control center.

In centralized MAC protocols, a node in the network acts as a coordinator which is responsible for scheduling, resource allocation and network management of the nodes in the network. Time is divided into slots which form super frames eventually. Centralized MAC protocols belong to dominated category of MAC protocols in UWB based networks at beginning.

IEEE 802.15.3 is the most typical representative of the centralized UWB based MAC protocol which is designed to support high-rate and low-cost connectivity in wireless personal area networks (WPANs)[14].

In this protocol, there is a coordinator (PNC) which functions as the central controller for the entire network in every Piconet. The coordinator manages all of the devices(DEV) in the Piconet.

Many centralized protocols are proposed by improving IEEE 802.15.3. To solve the collision problem between the accessing packets, Jiang Zhu et al proposed CC-MAC protocol introducing CDMA and ALOHA into 802.15.3 MAC protocol[15].

Ioannis Broustis et al proposed the concept of a multi-channel MAC protocol, in which frequency bandwidth from 3.10GHz to 10.6GHz is divided into multiple sub-bands in order to efficiently exploit the entire band[16]. But the protocol requires each pulse modulated to different frequency, which increases the complexity of the UWB transceiver. Furthermore, the communication requests are generated in a concentrated manner, which will cause higher probability of collision when the traffic is heavy. The protocol requires accurate synchronization which is difficult to achieve.

In paper[17], a MAC protocol that provides explicitly QoS support by optimizing resource utilization. The protocol includes a centralized resource allocation algorithm containing the scheduling algorithm and the resource control algorithm. The resource allocation algorithm differentiates between real-time traffic and Best effort traffic such that provide QoS for real-time traffic.

The complexity of centralized MAC protocols is low and thus is simple to implement due to the presence of a coordinator which achieves the scheduling orderly, and manages the communication among nodes in the network, However, it is not flexible to use such kind of protocols. The performance of the entire network will degrade dramatically when the coordinator fails.

To solve the aforementioned problems of centralized protocols, researchers turn to study distributed MAC protocols in UWB networks. All nodes are identical under distributed MAC protocols. The influence to the network performance is relatively little when nodes leave or join the network. Distributed MAC protocols in UWB networks are applied most commonly currently.

$(UWB)^2$ which adopts pure ALOHA access approach is specifically designed for low bit-rate UWB networks[18][19]. Based on the idea of separation of the control channel associated to a common TH code and data dedicated data channels associated to transmitter specific TH codes, and the prediction of synchronization sequence of transmitted packets, the probability of a successful synchronization is improved in the presence of multiuser interference.

SASW-CR(Slotted Aloha MAC with Sliding contention Window and Cooperative Retransmissions) adopts the Slotted Aloha to avoid carrier sensing and reduce packet collision, exploits differentiated contention windows mechanism to provide different levels of QoS for different traffic classes, and uses cooperative retransmission mechanism to improve the overall throughput of the network and reduce end-to-end delay[18].

Win, et al, adopted TH code in UWB networks for multiple users to share the same radio resources simultaneously[21]. Time-hopping code is exploited in the distributed MAC protocol proposed by Cuomo[22], in which joint optimization of distributed resource allocation, power and rate allocation are adopted.

Boudec [23][24][25] adopted interference mitigation technique at the physical layer and exploited dynamic channel coding at the same time. They proposed rate adaptive MAC protocol. By using dynamic channel coding, the sources are able to send simultaneously, causing rate reduction instead of collisions. Hybrid ARQ is introduced to the private MAC as well. Radunovic[26] further proposed cross-layer resource allocation strategies in which a combination of MAC layer power control, time scheduling and network layer routing is implemented.

Karapistoli et al proposed an UWB-based location-aided MAC protocol for wireless sensor networks, named LA-MAC in which distributed medium access control is realized by exploiting the precise position location provided by the UWB transmission technique[27].

X. Shen et al [10][11] proposed MAC protocols specifically designed for UWB networks, based on the exclusive region(ER) concept. To ensure the successful transmission, ERs surrounding the receivers and senders are reserved. The protocol allows multiple users to effectively and fairly share resources.

Hicham Anouar et al, proposed a fully distributed MAC protocol SEBROMA (self-balanced receiver-oriented MAC) which is a receiver initiated protocol such that a network-wide global synchronization is not required[28].

There is no unified control center in distributed MAC protocols in which each node is identical and self-organizing. The nodes in such UWB networks, however, synchronization among the nodes is a relatively large portion of time overhead, i.e. , long channel acquisition time. Furthermore, the nodes need to exchange the large amount of control information. Therefore, reducing channel acquisition time and control information transmission overhead when designing distributed MAC protocols in UWB networks is of critical importance.

III. The Design of URMPS Protocol

A. The Key Components of the URMPS Protocol

Based on above analysis, the receiver initiated MAC protocol with packet aggregation and selective retransmission is proposed. It mainly adopts the mechanisms as following.

(1) The receiver initiated communication request

MAC layer protocols in traditional wireless networks mostly exploits RTS (Request-to-send) frame transmitted by the sending node to initiate a communication request, in order to correctly transmit data. In UWB-based networks, however, the network receiver needs to search signal arrival time and adjust receiver's timing based on the searched results, which usually leads to the problem of long channel acquisition time. The reason is that signal transmission is carried out by using extreme narrow pulses. So very strict synchronization between the transmitting node and the receiving node is required. In general, traditional MAC protocol needs to determine status of the channel by carrier sensing before transmitting data. If the channel is busy, it should re-sense the channel sometime later. Otherwise, the sender that sends RTS message to request transmission is allowed to access the channel. Because there is no carrier presenting in UWB network link, it is inevitable to result in higher frame collision probability if the CSMA/CA based protocol is used. The long channel synchronization time and the invalid detection methods of channel status inevitably lead to poor performance in terms of throughput and delay as well as high energy consumption.

Therefore, this protocol introduces the mechanism that the receiver initiated communication request. In this protocol, a node does not sense the channel status before sending communication request. Instead, the protocol specifies that an idle node sends a URTR(UWB Ready To Receive) frame to initiate the communication request during idles slots. That's to say, when a node in the network is idle, the node will send a URTR message to indicate that it is ready to receive or forward data. The URTR message contains a synchronization sequence field. After receiving URTR message, the sending node can use this synchronization sequence contained in the URTR frame field to synchronize with the receiver in the coming process of message exchange if it intends to communicate with the receiver. So the synchronization occurs only between the sending node and the receiving node, and there is no need to synchronize among all of nodes in the network. The receiving node also does not need to perform the synchronization capture. Thus the high energy consumption caused by the long synchronization acquisition time is avoided. The URTR frame also contains a TH code field.

(2) The Packet aggregation mechanism and selective retransmission mechanism

As for the long synchronization capture time between the sender and the receiver in UWB-based networks, the packet aggregation mechanism is introduced to this protocol. By packet aggregation, the data packets are not transmitted one by one. Instead, several packets which are received by the MAC layer from the upper layer are combined into a larger frame before sending. This mechanism is mainly composed of the following three components:

● The classification of the packets

After receiving packets from the upper layer, a node firstly classifies the data packets according to certain rules. Then store them into the buffer queues. The classification is performed according to the destination address and the QoS requirements of data. Two queues are assigned for the packets from the upper layer. One queue is used to store the packets with QoS requirements and another queue is used to store the data packets without QoS requirements. When the node finds out that packets from the upper layer are without clear real-time requirements, the classification would be conducted only according to the destination address contained in data packets, and the packets with the same destination address will be buffered to the queue without QoS requirements. If the packets from the upper layer specify the real-time requirements, the packets will be buffered to the corresponding queue with QoS requirements according to the destination address and QoS requirements.

● The buffer management

After successfully establishing a communication link between the sending and receiving nodes, the sending node should select the packets stored in the queues in the following way. First, the node should find its corresponding buffer queue according to the MAC address of the destination node, then the node checks the QoS requirements which are indicated in the queues, the data packets in the QoS queue destined to the corresponding destination node will be sent in priority followed by sending the data packets in the queue without QoS requirements.

● The encapsulation of packets

The packets is encapsulated in such a way that multiple packets are packaged into a larger frame. Then the large frame is transmitted through physical layer. To support QoS requirements and avoid long delay caused by transmitting large data packets, the number of data packets from the queue with QoS requirement allowed to be encapsulated into one larger frame is limited to 10. After receiving UCTS frame, the sending node encapsulates the data packets in the queue into one frame immediately and then transmits them. For the packets in the queues without QoS requirements, all packets in this queue will be encapsulated into one frame. By the packet aggregation mechanism, only one time synchronization is needed for one large frame. Thus, channel capturing time required can be further reduced, which lead to better performance in terms of network throughput and transmission latency.

To provide reliability, the selective retransmission mechanism is exploited in this protocol. The receiver will send a UACK frame to the sender and specify the sequence number of the error frames in UACK, then the sender only resend the wrong data frame.

(3) The combination mechanism of mutually exclusive area and TH code

In order to mitigate the interference caused by concurrent transmission of multiple nodes, the network node reserves its mutually exclusive area in which concurrent multiple transmissions will collide by exchanging controlling frames URTR / URTS / UCTS between the receiving node and the sending node. The transmission of the data frame and UACK frame are completed thereafter. Thus, the interference between nodes in different mutually exclusive area can be solved since the interference outside the mutually exclusive area does not exist anymore. To further mitigate the interference of concurrent transmission, the TH code mechanism is introduced, the data from different sources use different TH codes so that the receiver can differentiate frames by TH codes.

The mutually exclusive area of a node is a region within which no simultaneous transmission is allowed. Otherwise, the collision will occur. We assume that an omnidirectional antenna is used in the protocol, so we can define the mutually exclusive area as a circular area around the receiving node, with its diameter D, illustrated as in Fig.1.

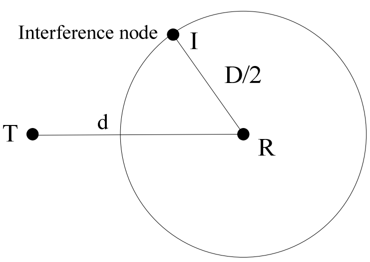

Fig. 1 Illustration of mutually exclusive area

In Fig.1, R, T, I denote a receiving node, a sending node, and an interfering node, respectively. The distance between the sending node and the receiving node is *d*, and the critical distance of the interfering and receiving nodes is *D/2*. If the distance between the actual position of interfering node and the receiving node $d_i < D/2$, we believe that any communication of the interference node will conflict with existing communication between the receiving node and the transmitting node. Otherwise, it is possible to allow the simultaneous communication of interfering node and the existing communication.

The standard capacity density of the UWB system is represented by the following formula [11]:

$$\overline{C} = \frac{C \pi d^2 L}{R} = x^{-2}\left(1 - 0.5\, erfc\sqrt{x^{\alpha}\frac{W}{R}}\right)^{L} \quad (1)$$

In the formula, $x = d_i/d$, L indicates a frame size, R is the bit rate, W *is* the transmission bandwidth, C is the capacity of the UWB system. We can see from formula (1), $\overline{C}$ will tend to infinity when x tends to 0. In this case, d_i tends to 0, which means that the interfering node and the receiving node will coincide. So we consider looking for a suitable $\overline{x}$ so that $\overline{C}$ will increase with increasing x when $x < \overline{x}$, and $\overline{C}$ will decrease with increasing x when $x > \overline{x}$. We can see from the formula (1) that x greatly influence the capacity density of the entire system as the bit rate and bandwidth are constant. It is very important to choose the appropriate x for improving the capacity density of the entire system. J. Ding[28] et al have given the appropriate method to determine the appropriate distance d_i between the interfering node and the receiving node according to $\overline{x}$, and point out that the appropriate distance is *D/2*.

B. The Detail Description of the URMPS Protocol

Fig.2 shows how a link between the source node and the destination node is established. Next we will elaborate this process.

(1) An idle potential receiving node sending a URTR frame. When some node R in the network is ready to receive data, this means the node is idle at this moment and there is no data to send or to forward. By sending a URTR frame in a randomly selected slot the node indicates that it is able to receive or forward data.When node located within the communication range of node R receives a URTR message successfully, it will determine whether to send the URTS message to the R node according to its communication requirements.

(2) The source node sending a URTS frame. After successfully receiving URTR message from the node R, the node T first determines whether the node R is in its mutually exclusive area according to the received signal strength of URTR message if it has data to send. Node T will discard the URTR information if the receiving node R is not in its mutually exclusive area. Or else, the node T will determine whether the TH code used in URTR message repeats with the one in communication state table, and will discard the URTR frame if repeats. Or else, it will send a URTS frame to the node R to compete the channel after backoff some random time slots. If the node T has no data to send after receiving URTR message successfully, it will send a short wavefront so that the node R can tell whether there is data it needs.

(3) The receiver replying a UCTS frame. The node R will reply a UCTS message to node T after receiving a

URTS frame successfully, to indicate communication link between the two nodes is established successfully, and data can be transferred over the link established.

(4) The source node sending a DATA frame. After receiving UCTS message successfully, the sending node T will encapsulate multiple packets into one frame and then send it out.

(5) The receiver replying a UACK frame. After correctly receiving the data packets transmitted by the node T, the node R will reply a UACK frame to the node T to acknowledge. Otherwise, if the received data frames include some erroneous data packets, the node R will indicate in the UACK frame. After finishing sending the UACK frame, node R will continue to wait for receiving data frames until the moment having successfully received all the data packets stored in the buffer of node T or the communication is timeout.

The protocol should also consider the cases of frame lost in any above stage. Fig.2 illustrates a normal process of data frame transmission.

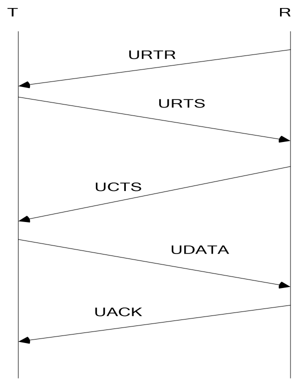

Fig.2 The interaction diagram of protocol information

IV. SIMULATION RESULTS

The simulation was conducted over NS-2.29[30] and the operation system is Ubuntu10.10. The specific parameters of the simulation scenarios are shown in Table 1. The protocol for comparison is S-MAC [31]which is the classic MAC protocol of wireless sensor networks.

TABLE 1
SIMULATION PARAMETERS OF THE PROTOCOL

Simulation parameters	values
Bandwidth(Mbps)	100
Channel model	Tarokh
Data flow	CBR stream
Maximum number of packet assembly packets	10
Transmission distance(meters)	3
Modulation schemes	PPM
Antenna model	omni-antenna
The number of nodes	20
The maximum contention window number	31

Tarokh channel model[32]listed in Table 1 is implemented based on the 802.15.3 protocol. In this channel model, the method of evaluating the transmission distance and adjusting sending power is defined. The simulation results mainly concentrate on the network throughput and network latency.

A. The Network Throughput

The network throughput reflects data transmission ability of the whole network. Here it refers to the average throughput(Mbps), namely the amount of data transmitted successfully per unit time.

Fig.3 shows the throughputs of URMPS and S-MAC under the different packet generation rates. The results show that there is an evident improvement in terms of the average throughput of the system using URMPS compared to S-MAC, which coincides with the design objective of protocol. This is mainly due to the combination mechanism of mutually exclusive area and TH code adopted in URMPS protocol, both of which can support concurrent transmissions better than S-MAC. This, in turn, generate higher throughput effectively. However, for the S-MAC protocol, the interference between the multiple access nodes is controlled generally through the power control. Because the transmitted power of UWB signal is limited strictly by FCC(Federal Communication Commission), the power control for reducing interference is not so efficient. If the concurrent transmissions among multiple nodes is not appropriately coped with well, the collision between packets will exacerbated and it is difficult for receivers to receive packets correctly, which directly lead to lower network throughput.

Fig.4 and Fig.5 have respectively shown the simulation results of the network throughput for URMPS and S-MAC under a constant packet generation rate. In the figure, a represents the data packet generation rate. The results in the figure indicate that the network throughput of URMPS is higher than that of the S-MAC protocol as the data size is relatively small. But the difference is slight, that is because the packet aggregation mechanism exploited in the protocol limits the maximum number of aggregation packets, which is 10 at a time. With the increase of data frame size, however, the benefit brought by packet aggregation mechanism is more obvious. From the figures, it can be seen that the throughput of URMPS is visibly higher than that of the S-MAC when the single packet size reaches 2000bytes. The reason for this is that the packet aggregation and selective retransmission are adopted in URMPS. So it generally needs one synchronization overhead when transmitting multiple packets, which can further reduce channel acquisition time. Selective retransmission is exploited to reduce overhead, too. Both mechanisms contribute to enhance throughput.

B. Network End-to-end Delay

Here, delay refers average end-to-end delay time, i.e. the average of the delay between multiple sending and receiving nodes.

Fig.6 is a comparison chart about delay of URMPS and S-MAC protocol under the different packet generation rates. From the chart, it is can be seen that both of URMPS and S-MAC experience an increasing trend of average end-to-end delay with the increase of the packet generation rate (the unit is pkts/s). When the packet generation rate reaches 20pkts/s, the delay remains substantially stable and the average end-to-end delay of the protocol is far lower than that of S-MAC in the case of a relatively small data packet. This is due to the receiver initiated communication request which reduces channel capturing time, and the packet aggregation mechanism by which multiple packets transmission does not require multiple exchanges of control frames, and TH code and mutually exclusive area mechanisms which reduce collisions during data transmission between nodes.

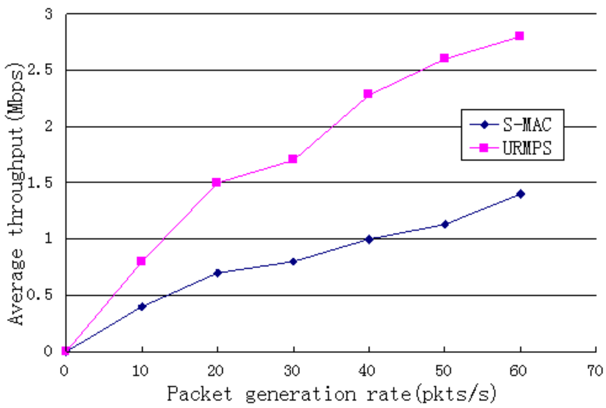

Fig.3 the network throughput versus packet generation rate

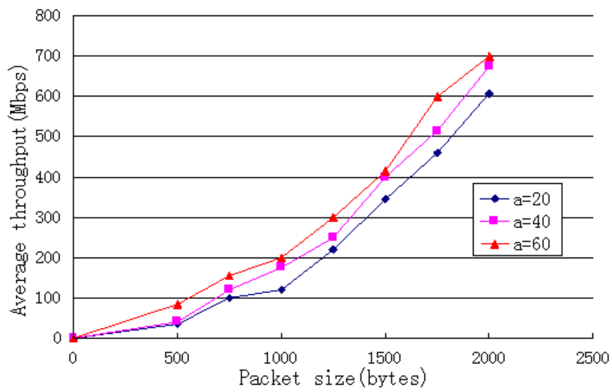

Fig.4 the network throughput of URMPS versus the packet size

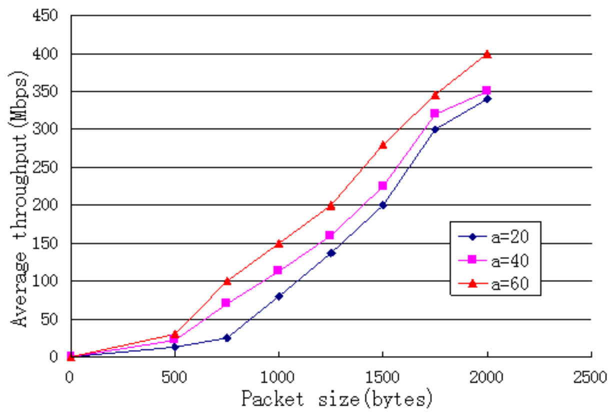

Fig.5 the network throughput of S-MAC versus the packet size

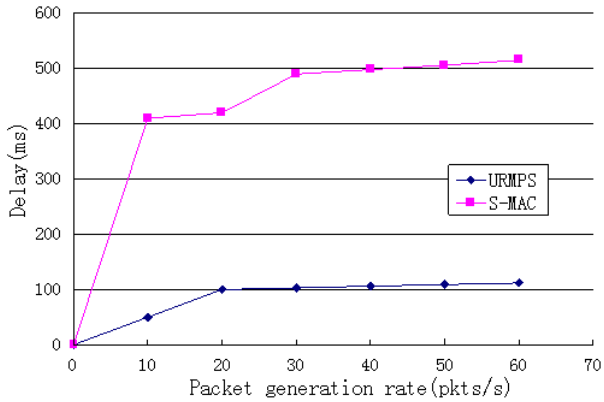

Fig.6 end-to-end delay versus the packet generation rate

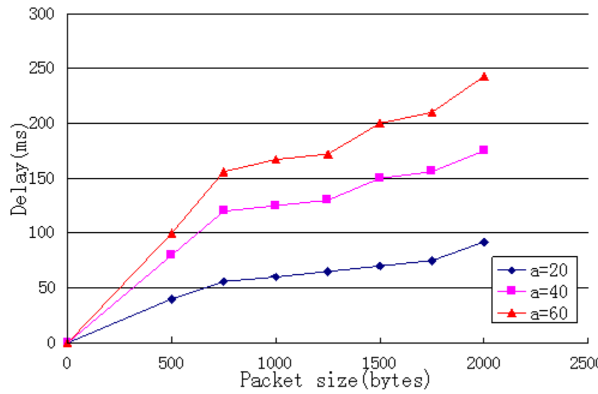

Fig.7 average delay of the URMPS versus the packet size

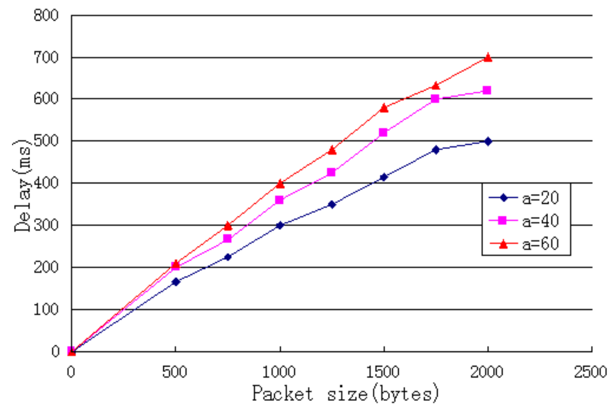

Fig.8 the time delay of the S-MAC versus the packet size

Fig.7 and Fig.8 show the simulation results about network delay of URMPS and S-MAC protocol under a constant packet generation rate(a is a constant), The results shown in the Figure indicate that both of the two protocols experience an increasing trend of average end-to-end delays with the increase of the packet size. However, the performance of URMPS obviously outperforms that of the S-MAC protocol in terms of delay. This is mainly due to the receiver initiated communication request and packet aggregation exploited in URMPS, which can effectively reduce the channel synchronization time. However, the S-MAC protocol exploits periodic listening and sleeping, and if a node want to send data packets to its neighbor, the neighbor node must be listening state, which results in some delay.

The average end-to-end delay of URMPS is less than 100ms when the data packet size is relatively small, e.g., less than 500 bytes per packet. So the protocol is basically able to meet the real-time communication requirements of wireless multimedia sensor networks.

V. Conclusion

In this paper, the proposed protocol is a MAC layer protocol specifically designed according to the characteristics of UWB technology. The protocol uses the receiver initiated communication request mechanism. TH code specified by the receiver and synchronization signals for the potential sending node is specified by the receiver in advance. To overcome the problem of high energy-consuming and larger delay occurred in the process of signal synchronization, we exploit the URTR frame to initiate the communication process from the receiver side. In addition, the protocol uses packet aggregation and selective retransmission mechanisms which further improve throughput and reduce latency. Based on the above mechanisms, the protocol is more suitable for the occasion of the multimedia information delivery.

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