A Primary Adaptation of the W-CHAMB Protocol for Gigabit WPANs

Rui Zhao, Bernhard Walke, Michael Einhaus and Georgios Orfanos
Chair of Communication Networks, RWTH Aachen University,
Kopernikusstr.16, D-52074, Aachen, Germany
E-mail: {rui, walke, ein, orf}@comnets.rwth-aachen.de

ABSTRACT

High speed WPANs are intended to provide multi-media and multi-megabyte transmission services over relatively short distances for a wide range of devices. The long term goal of future high speed WPANs is to support transmission with a data rate of up to 2 Gbps. The W-CHAMB protocol is a link layer protocol for next generation WLANs. It is able to perform multi-hop delivery of high quality multi-media services in a fully distributed manner. In this article, we adapt the W-CHAMB protocol for Gigabit WPANs. The analytical results on the traffic performance and system capacity indicate that the adapted protocol is able to support high amounts of high quality multi-media transmission services in multi-hop Gigabit WPANs.

Keywords

WPAN, Gigabit, QoS, multi-hop operation, multi-media, ad-hoc networks, decentralized protocol, TDMA.

I. INTRODUCTION

Wireless personal networks (WPAN) are used to provide ad-hoc connectivity among a wide range of consume electronics and portable communication devices in short ranges. It requires little or no infrastructure and only allows low cost, low complexity and power efficient medium access control (MAC) and physical layer (PHY) implementations. As the first WPAN technology, Bluetooth achieves a mass success in the market. The next generation of WPANs will support multi-media traffic which requires high data rates and Quality of Service (QoS) guarantee. Potential applications include high quality real-time audio and video deliveries, and multi-megabyte local file transfers.

The IEEE 802.15.3c study group [2] is formed to study the alternative PHY working on 24 to 60 GHz frequencies to provide high data rates from 0.3 to 2.2 Gbps in home environments. However, transmission on such high bands suffers strong propagation attenuation and has a low obstacle penetration rate too. Multi-hop forwarding offers an efficient way to reduce the required transmitting power to a reason level by dividing a long transmission distance into several shorter ones and extend the radio coverage. Therefore, implementing multi-hop operation in WPANs helps to achieve cost efficiency and bring more convenience.

The Wireless Channel-oriented Ad-hoc Multi-hop Broadband (W-CHAMB) [3, 4, 5] protocol is a fully distributed control protocol. It is based on Time Division Multiple Access (TDMA) technology, working on a single frequency channel. A W-CHAMB network is formed in an ad-hoc manner with ability to support QoS in multi-hop operation. The W-CHAMB protocol was previously designed for wireless LAN (WLAN) applications. In the paper, we adapt it to support Gigabit WPANs and investigate the traffic performance by analytical approaches.

The rest of paper is organized as follows: We shortly describe the W-CHAMB protocol in Section 2. After that, we present our adaptive scheme and the analytical results as well. We finally conclude in Section 4.

II. THE W-CHAMB PROTOCOL

W-CHAMB is a TDMA system. Transmission takes place in periodic time slots. The operation of a network requires that stations are synchronized. Any network station can communicate with any other station as long as they are in range of one another. It may also allow multi-hops to route messages from any station to any other station on the network.

A. Protocol Stack

Fig. 1 describes the protocol stack of the W-CHAMB system. The W-CHAMB protocol consists of three parts. The W-CHAMB MAC protocol manages the access to the radio medium, the use of the TDMA channels, elimination of hidden stations and implementation of synchronization. The W-CHAMB Radio Link Control (RLC) protocol provides data transfer service to the upper layer in both acknowledged mode (AM) and unacknowledged mode (UM). The W-CHAMB Radio Resource Control (RRC) protocol takes care of wireless resource related management algorithms like Call Admission Control (CAC), power control and dynamic frequency selection.

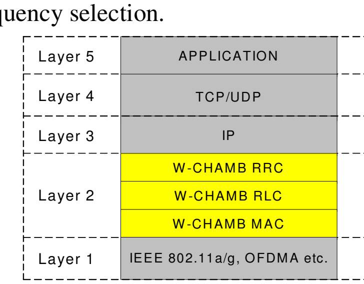


Fig. 1: Protocol stack of the W-CHAMB system

B. MAC Frame and Energy Signals

The MAC frame and waveform of energy signals are shown in Fig. 2a. Energy signals, in-band busy tones [7], play important roles in W-CHAMB. An energy signal occupies a short time slice, for instance 6 µs. Energy signals are classed into two types: Access-E-Signal (AES) and Busy-E-Signal (BES).

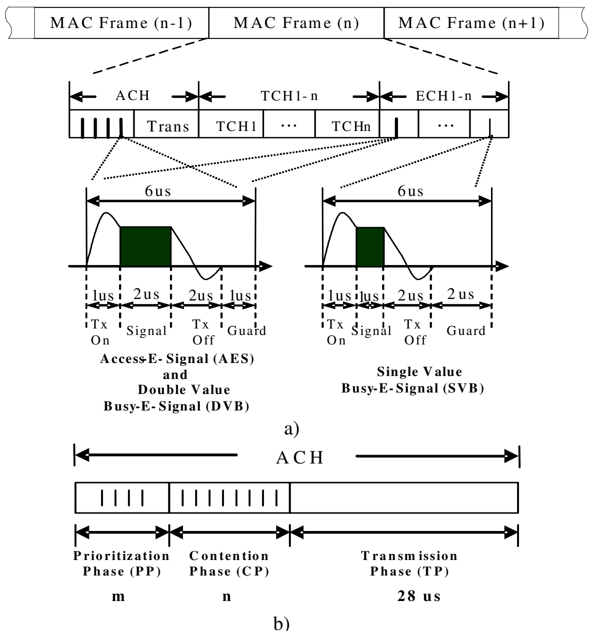


Fig. 2: a) MAC frame and waveforms of energy signals; b) ACH structure.

W-CHAMB is a distributed TDMA/TDD system. A solution for synchronization is given in [6]. Each MAC frame contains a number of time slots. Time slots are logically grouped into 3 types. The first type is the Access Channel (ACH), in which Access-E-Signals are transmitted to compete for an access right to reserve traffic channels. The second type is called Traffic Channel (TCH), each slot carrying one data packet per MAC frame. The last type is the Echo Channel (ECH). In a MAC frame, the number of ECH slots is the same as that of the TCH slots. Each ECH slot is exactly paired with one TCH slot. An ECH slot is used by the receiver to signal the occupancy of the corresponding TCH by transmitting a Single Value Busy-E-Signal (SVB) in order to calm down hidden stations and if necessary, by transmitting a Double Value Busy-E-Signal (DVB) to request the reverse transmission opportunity, i.e. the TCH in TDD mode of operation.

Busy-E-Signals are used in the ECH, while Access-E-Signals are used in the ACH. Busy-E-Signals are categorized as DVB and SVB according to the signal length. An Access-E-Signal has the exact waveform of a DVB.

The critical parameters like the number of TCHs, waveform of an energy signal, number of energy signals and length of a MAC frame are subject to change with PHY layers and applications. All the MAC frame related parameters are never changed during operation. An example of parameters appears in Fig. 2 by assuming the IEEE 802.11a PHY layer and the WLAN application.

C. *Prioritized Access*

An ACH slot has three phases: Prioritization Phase (PP), Contention Phase (CP) and Transmission Phase (TP), as shown in Fig. 2b. A number of binary Access-E-Signals are used in the first two phases to implement a prioritized access mechanism. The PP is the QoS related contention phase. The setting of CP is to guarantee with a high probability that there is only one winner under a heavy contention. Assume that the number of binary Access-E-Signals in PP and CP of an ACH is m and n, respectively. The number m is associated with the amount of QoS levels, n with the station density. As long as a station has packets in its transmit buffer, it would initialize a contention process to try to send out a request packet for reserving TCH(s) for a one hop connection or to broadcast a packet like a Beacon via the ACH.

The contention is performed as follows:

1) Each station uses the QoS level specified in the buffered packets as the contention number for PP. The amount of QoS levels is up to 2^m. The higher the number, the higher the access priority.
2) A station checks the number bit by bit, when the bit is 1 it sends an energy signal, for 0 it listens. The most significant digit is transmitted first.
3) During a listening period, once hearing an energy signal, the contending station knows that it has lost the contention in the current MAC frame. It must cancel the rest of its pending energy signals and contend again in the future.
4) Surviving stations of PP use the same listening and sending scheme again to contend in CP by a number from $[0, 2^n-1]$.
5) The final winner of the previous phases then sends out a packet in the TP.

D. *TCH Reservation and Hidden Stations Solution*

When a station wishes to transmit packets, it firstly checks the channel status. In case the amount of available TCH(s) observed at its own location meets the traffic need, it would contend for an access in the ACH and if it wins, it broadcasts a request packet for TCH(s) reservation containing the receiver address, QoS-related traffic specification (QTS) and a list of proposed TCH slots in the TP of ACH. After receiving the request packet, the destination station makes the decision whether to accept the request or not by evaluating the received QTS and the free TCH slots available at its location. In case of acceptance, the receiver transmits SVB(s) in ECH(s) corresponding to the accepted TCH(s). Both the originator and nearby stations of the receiver obtain valuable information from the SVB(s). For the originator, it knows that the TCH(s) have been reserved. For the nearby stations, they know that the respective TCH(s) are in use and they cannot use them right now, therefore potential hidden stations are calmed down.

E. *Transmission and On-demand-TDD*

Once TCH(s) have been reserved for a one hop connection, the sender uses one or some of them to send out its data packets. No matter whether the receiver correctly receives the packets or not, it replies with the SVB(s) in the related ECH(s) to signal the occupancy of the respective TCH(s) in its environment. In case the receiver has some data to send back, it transmits a DVB instead of SVB on the corresponding ECH. If the sender senses the DVB, from the next frame on, it stops the transmission in the respective TCH(s) and takes the charge of transmitting energy signals in the ECH(s). And the receiver shall send out packets via the reserved TCH(s). This scheme is called On-Demand-TDD. Fig. 3 shows an example of the process.

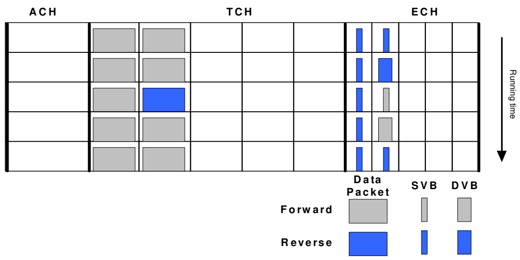


Fig. 3: An example of transmission process and On-demand-TDD.

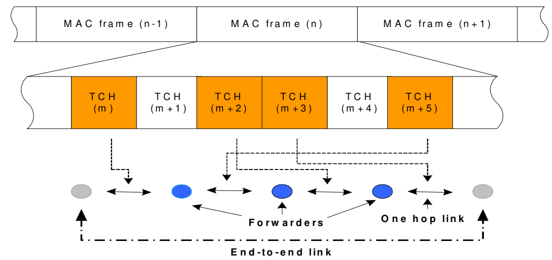


Fig. 4: Multi-hop forwarding might take place in a same MAC frame.

F. TCH Release

A TCH is freed when meeting the following conditions:

1) There is no packet in the TCH transmit buffer.
2) The hang-on time specified for the TCH is expired.

G. Packet Multiplexing

A TCH established between adjacent stations is used to multiplex any packets transmitting on the route. The sequence of transmission of packets competing for a TCH is according to their QoS priorities.

H. Multi-hop Operation

A multi-hop connection consists of multiple one-hop connections in tandem that each is independently controlled. As shown in Fig. 4, owing to the TDMA structure, the hop-to-hop forwarding of a multi-hop transmission might take place simultaneously in different TCHs of a MAC frame, helping to obtain very low end-to-end packets delays.

I. Synchronization

A primary solution is given in [6]. We developed an enhanced scheme. Due to limited page space, we shortly describe the scheme in this paper:

1) Beacon packets carrying time information are broadcasted periodically. Each station might be a potential Beacon generator. Recipients update their time by analyzing the received Beacons.
2) The access mechanism ensures that there is only one winner in almost every contention, which is important to guarantee that a Beacon appears timely over the air.
3) The clock shift compensation algorithm helps to mitigate the clock skews.
4) For achieving the synchronization in a multi-hop network, an adaptive algorithm is developed to help find out the stations which are located in "right" places. Then those stations are assigned with more responsibilities to send out Beacons. The synchronization accuracy is improved a lot with the help of this algorithm.

J. W-CHAMB RLC

W-CHAMB RLC offers two kind modes of service to the upper layer: UM for connectionless point-to-point, multicast and broadcast applications; AM for reliable point-to-point applications. In short, AM provides the in-sequence error free data services to the upper layer. A selective repeat Automatic Request (SR-ARQ), by making use of the On-demand-TDD feature offered by the MAC protocol, is implemented as the link layer error and flow control scheme for AM [5].

III. Adaptation for Gigabit WPANs

The PHY for Gigabit WPANs is still under research [2]. The following assumptions are made for this study based on state-of-art PHY technologies [8] and usage models [9]:

1) Transceivers work on 60 GHz. The PHY data rate is 1.08 Gbps. It is achieved by using the Orthogonal Frequency Division Multiplexing (OFDM) technology on a single frequency channel.
2) The modulation scheme is Quadrature Amplitude Modulation (QAM) 3/4. The OFDM symbol interval, coded bits per symbol and coding rate are 800 ns, 1152 bits and 3/4, respectively.
3) The Rx-to-Tx turnaround and energy signal detect time are lower than 2 μs and 1 μs, respectively. A guard time of 0.5 μs in an energy signal and a PHY packet data unit (PDU) satisfies the WPAN requirement. The overhead of a PHY PDU is 6 μs, including Automatic Gain Control (AGC), Synchronization (SYN), Tx power on (off) and guard time.
4) The potential traffic services, their traffic behaviors and QoS requirements are listed in Tab.1:

Traffic	Load (Mbps)	Packet size (bytes)	Max Delay (ms)	Max Packet loss rate (PLR)
VoIP	0.0224	120	60	6%
Video conference	Mean:0.512 Max:2.0	512	100	0.1%
DVD	9.8 peak	1500	200	10^-7
HDTV	19.2-24	1500	200	10^-7
Local FTP	30	1500	-	-

Tab. 1: Potential traffic services, their traffic behavior and QoS requirements.

A. The MAC Frame Structure and Energy Signals

An energy signal suitable for Gigabit WPANs can be designed as 4.5 μs long, comprising the Tx power on (off) time, Signal and guard time. A TCH contains the overhead and period for a MAC PDU. Fig.5 shows the shapes of energy signals and TCH slots.

The numbers of energy signals in the PP and CP of an ACH are 4 and 8 respectively, in order to support up to 16 contention levels and a reasonable station density. The lengths of packets which are transmitted in the TP of an ACH like Beacons and request packets are less than 100 bytes; therefore a period of 8 μs including the overhead is sufficient for TP. Tab.2 describes the key parameters of the MAC frame.

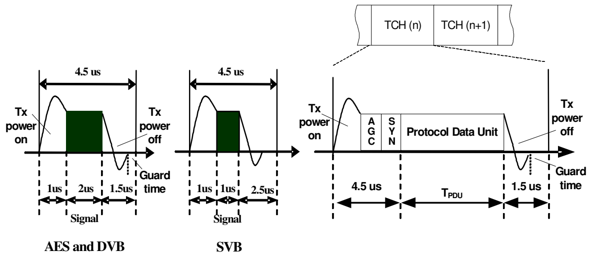


Fig. 5: Energy signals and TCH slots.

Number of energy signals in PP (ACH)	4
Number of energy signals in CP (ACH)	8
Length of TP in an ACH	8 μs
Length of an energy signal	4.5 μs

Tab. 2: Key parameters in a MAC frame.

Let T_M be the maximum throughput in the MAC layer under zero packet error rate (PER) condition, N_{TCH} the number of TCHs in a MAC frame, N_{ECH} the number of ECHs in a MAC frame, T_{MAC} the time period of a MAC frame (unit: μs), L_{PDU} the longest MAC PDU in bytes fitted in a TCH, T_{PDU} the time period of L_{PDU} (unit: μs). From the definitions, we have:

$$L_{PDU} = \frac{T_{PDU} \times 1.08 \times 10^{9} \times 10^{-6}}{8} \tag{1}$$

$$T_{MAC} = 4.5 \times (4+8) + 8 + (6 + T_{PDU}) \times N_{TCH} + 4.5 \times N_{ECH} \tag{2}$$

$$T_{M} = \frac{L_{PDU} \times N_{TCH}}{T_{MAC}} \tag{3}$$

$$N_{ECH} = N_{TCH} \tag{4}$$

Using (1) and (4) into (2) yields:

$$T_{MAC} = 62 + (10.5 + 7.4 \times 10^{-3} \times L_{PDU}) \times N_{TCH} \tag{5}$$

The relationship between the TCH number per MAC frame and T_M under various L_{PDU} values is plotted in Fig. 7 following Eq. 3. It can been seen that in order to achieve a reason T_M under the Gigabit rate, L_{PDU} should be long enough, saying at less over than 1000 bytes. Meanwhile, the more TCH number per MAC frame, the better traffic performance in multi-hop operation as suggested in Fig. 4. On the other hand, a big TCH number per MAC frame and a long TCH duration result in a longer MAC frame, which adversely increase the access time of a station and multi-hop forwarding time. Fig. 7 depicts how a TCH number and L_{PDU} affect the MAC frame length following Eq. 5.

When transmitted in a real wireless channel, a longer packet tends to get corrupted easily than a short one. Let P be the PER of a PDU, L the length of the PDU. L-PDU and S-PDU represent the long PDU and short PDU, respectively. It is obtained that:

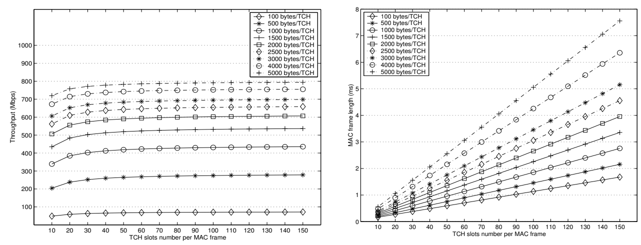


Fig. 7: The impact of the TCH number per MAC frame on the maximum throughput and the MAC frame length under various L_{PDU} values.

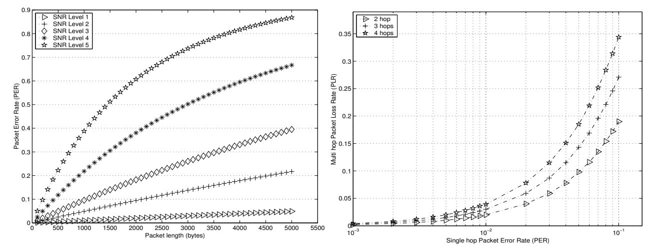


Fig. 8: Left: the impact of the packet length on PER under various SNRs. Right: end-to-end PER increases significantly with the number of hops when no error control scheme is used.

$$P_{L-PDU} = 1 - (1 - P_{S-PDU})^{\frac{L_{L-PDU}}{L_{S-PDU}}} \tag{6}$$

For a given PDU, a lower PER can be achieved under a relatively high Signal Noise Ratio (SNR) environment. We assume five SNR levels in this paper by relating SNRs to PERs of the PDU with a length of 100 bytes. The SNR level 1, 2, 3, 4, 5 correspond with PERs of 0.001, 0.005, 0.01, 0.025, 0.05, respectively. From the literature [8], the SNR level 3 is the most possible SNR value in high rate WPANs. We reveal the impact of the PDU length on PER in Fig. 8 by putting the assumed values into Eq. 6. As shown in Fig. 8, in high SNR environments, saying level 1 and level 2, a longer PDU still can be correctly delivered in a high probability. However, acquiring a high SNR needs costly efforts like increasing transmitting power or using powerful antenna. While in level 4 and 5 environments, a longer PDU is apt to incur a higher PER, which value actually leads to a lower throughput and longer packet delay.

When considering multi-hop operation, the packet loss rate (PLR) issue becomes more serious. When no error control scheme is used, the end-to-end PLR of a given PDU can be expressed as:

$$PLR = 1 - (1 - PER)^{N_{hop}} \tag{7}$$

Where N_{hop} is the number of hops that a PDU is transmitted over. Eq. 7 is plotted into the left graph of Fig. 8 to exhibit the relation between multi-hop PLRs and PERs. End-to-end PERs increase significantly with the number of hops. With a PER of 0.1, the PLRs in 2, 3, 4 hops are 0.19, 0.27 and 0.344, respectively.

Based on the above analyses, we conclude that firstly, MAC PDUs should be long enough to achieve a high transmission efficiency. At the same time, the length of PDUs also should be limited into the area that would not cause a high PER and a long MAC frame. From Fig. 7, a reasonable MAC PDU should be over than 1500 bytes long. While a MAC PDU should be less than 3000 bytes in order not to incur PERs more than 0.25 under the normal SNR level. Secondly a bigger TCH number per MAC frame offers a better QoS and multi-hop operation support. However a longer MAC frame length caused by it deteriorates the delay performance as well as the access time. By considering the traffic QoS requirements given in Tab. 1 and assuming that the maximum supported number of hops is 4, we deduce that the TCH number per MAC frame should be less than 80. When the MAC PDU length is around 1500 to 3000 bytes, 60 is a good compromise.

B. Multiplex

The conclusion that the maximum MAC PDU fitted in a TCH for Gigabit WPANs should be from 1500 to 3000 bytes long has a great impact on designing the transmission scheme. By taking a close look at traffic service behaviors in Tab. 1, we can find that packet sizes of various services are from 100 to 1500 bytes. In a MAC entity, unlike the conventionally used rule to fragment a high layer PDU into several short MAC PDUs, in Gigabit WPAN systems, several high level PDUs should be combined into a MAC PDU before transmitting. Fig. 9 illustrates the multiplex idea.

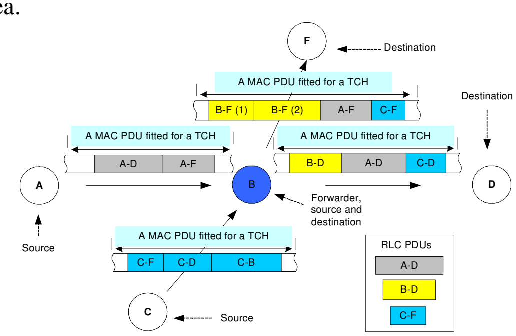


Fig. 9: Multiplex of RLC PDUs from different sources into a MAC PDU.

Five stations appeared in the figure is a part of a WPAN. Station A, C and B are sources, while B, F, D are destinations. Station B also works as a forwarder. Each source constructs a MAC PDU by multiplexing RLC PDUs for different destinations into a MAC PDUs. The forwarder picks up the RLC PDUs from different sources (including its own RLC PDUs) to combine a MAC PDU according to the next direct destination. With the multiplex scheme, the channel utilization is greatly enhanced. For instance, a single TCH can be used for delivering 12 and 25 VoIP traffic flows when the maximum MAC PDUs are 1500 and 3000 bytes long respectively.

C. Traffic Performance and System Capacity

We mainly concern about the delay performance in multi-hop operation. As indicated before, the MAC PDUs in Gigabit WPAN should be long enough in order to achieve a high efficiency, which adversely cause bigger PERs. Without using the error control scheme like ARQ, it is hardly to satisfy the PLRs required by various traffic services listed in Tab. 1. We analyze the multi-hop delay performance by assuming that a SR-ARQ protocol is used for all the traffic flows. The receiver acknowledges the reception periodically and sender retransmits the lost MAC PDUs immediately after receiving an acknowledgment report. It is assumed that the retransmit time is 10 and acknowledgement packets are always correctly delivered. Let T_{Ack} be the acknowledgement period (unit: MAC frames), p(n) the probability that a MAC PDU is successfully transmitted at the nth retransmitting time, D_{1hop} the mean one hop packet delay (unit: MAC frames), D_{e2e} mean end-to-end packet delay, E[x] the expectation of a random variable x. The mean packet delay can be expressed as:

$$D_{1hop} = E\left[(n-1)\bullet T_{Ack}\right] = P(1)\bullet 1 + \sum_{n=2}^{10} P(n)\bullet(n-1)\bullet T_{Ack} \tag{8}$$

where

$$P(n) = (1-PER)\bullet PER^{n-1} \tag{9}$$

Since a MAC PDU is quite long (from 1500 to 3000 bytes), T_{Ack} should be set as a small number in order to save transmit buffer. We further assume that multi-hop forwarding takes place simultaneously in a MAC frame as shown in Fig. 4. It can be simply expressed that:

$$D_{e2e} = N_{hop}\bullet D_{1hop} \tag{10}$$

We plot Eq. 10 into Fig. 10 by assuming T_{Ack}=10 MAC frames.

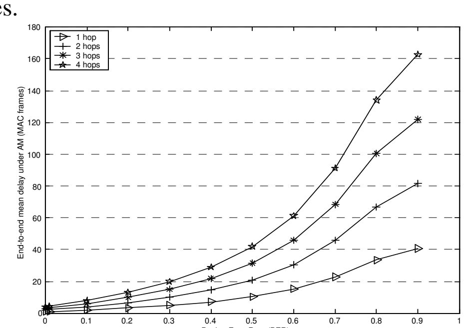


Fig. 10: The impact of PER on the mean end-to-end packet delay under AM.

It can be seen from the graph that D_{e2e} increase slightly with PERs in the single hop case, but remarkably in the multi-hop cases. In order to meet the delay requirements specified in Tab. 1 under multi-hop operation, PERs should be within a certain area.

We further plot the impact of the MAC PDU length on D_{e2e} into Fig. 11 by applying the results from previous graphs and assuming that the SNR is level 3. The MAC PDU length has less impact on the single hop case: the D_{e2e} values in all PDU lengths are small enough to satisfy the delay metric of QoS requirement. But the D_{e2e} values go up significantly with the number of hops. In the worse case shown in the graph, the D_{e2e} is around 35 ms when a 3000 bytes long MAC PDU travels over 4 hops. For a given traffic service, for instance DVD traffic, whether the transfer with a mean delay of 35 ms can still satisfy the specified PLR (10^-7), needs to be further investigated (a PDU will be dropped when its packet delay is over than the maximum tolerable delay).

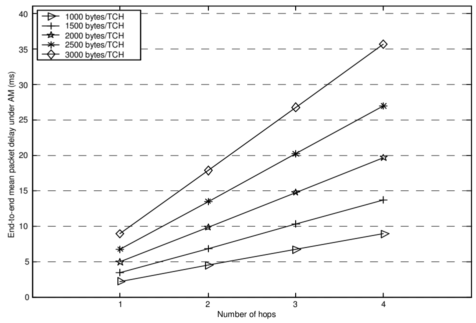


Fig. 11: The impact of the MAC PDU length on the mean end-to-end packet delay under AM.

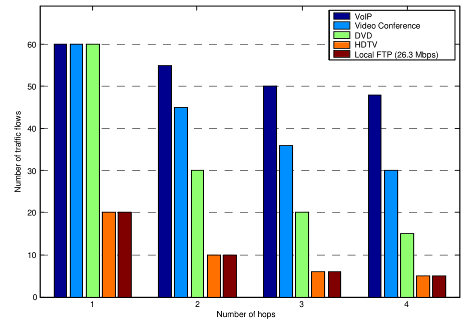
Now we estimate the system capacity for different traffic services when the maximum MAC PDUs are 1500 and 3100 bytes long, respectively. The system capacity here means the maximum number of traffic flows which can be transmitted in parallel in a network. Assume the SNR in the network is level 3 and a TCH is never released once reserved. The one hop ARQ throughput T_{ARQ} can be roughly calculated by Eq. 11 [1]:

$$T_{ARQ} = (1 - PER) \times T_M \qquad (11)$$

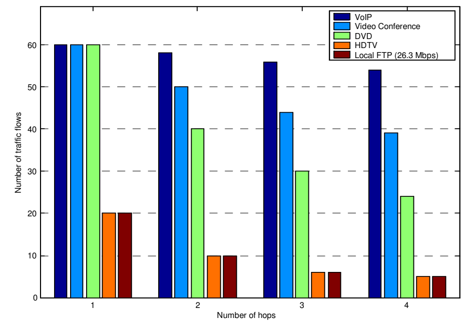
Assuming the TCH number per MAC frame is 60, it can be read from Fig. 7 and 8, when the MAC PDU length is 1500 bytes, the MAC frame lengths and PER of a MAC PDU are 1.376 ms and 0.14, respectively. While when the MAC PDU length is 3100 bytes, the values are 2.096 ms and 0.26. Using one TCH, a transmit pair can achieve ARQ throughputs of 7.5 and 8.5 Mbps when the MAC PDU are 1500 and 3100 bytes long, respectively. When RLC PDU lengths are shorter than the maximum MAC PDU length, a TCH can be used to multiplex several flows. For delivering high load traffics like HDTV and local FTP flows, several TCH should be used together to transmit a data flow. Fig. 12 a) and b) show the system capacity when the maximum MAC PDUs are 1500 and 3100 bytes long respectively. From the graphs, we can find that in both cases, a network can deliver large numbers of various traffic services in multi-hop operation. The supported number of traffic services decreases with number of hops. The decreasing rate of high load traffic flows is sharply than that of low-load traffic flows. The longer a maximum MAC PDU, the more RLC PDUs can be multiplexed into it. This is why a network supports more low-load traffic like VoIP, video conference and DVD flows when the maximum MAC PDU is 3100 bytes long. On the contrary, a network supports same number high-load traffic such as HDTV and local FTP flows for both the maximum MAC PDU cases when several number TCHs are used to transmit a single flow.

IV. Conclusions

We primarily adapt the W-CHAMB protocol for Gigabit WPANs. The traffic performance and system capacity are investigated by analytical approaches. The results suggest the adapted protocol is able to support larger number of various real-time traffic services in multi-hop operation. It is a suitable link layer protocol for future Gigabit WPANs with wide radio converges at low prices.



a)



b)

Fig. 12: System capacity: a) the maximum MAC PDU is 1500 bytes long, b) the maximum MAC PDU is 3100 bytes long.

References

[1] B. Walke, “Mobile Radio Networks Networking and Protocols,” 2nd Edition John Wiley & Sons 2001.

[2] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), "IEEE P802.15.3c Project Authorization Request (PAR)," P802.15-04/250r4, Oct. 2004.

[3] B. Xu and B. Walke, “A New Air Interface Concept for Wireless Multimedia Communications beyond the 3rd Generation,” Wireless Personal Communications Vol. 23, No.1, pp. 121-135, Oct. 2002.

[4] M. Lott and B. Walke, “Performance of the Wireless Ad hoc Network W-CHAMB,” in Proc. European Wireless (EW’99), Munich, Germany, Oct. 1999.

[5] R. Zhao and B. Walke, “Traffic Performance of the Wireless Channel-Oriented Ad-hoc Multi-hop Broadband System,” in Proc. IEEE VTC Fall 2004, Los Angeles, USA, Sep. 2004.

[6] R. Zhao and B. Walke, “A Synchronization Scheme for the Wireless Channel-Oriented Ad-hoc Multi-hop Broadband System (W-CHAMB),” in Wireless World Research Forum, Zurich, Switzerland, Jul. 2003.

[7] F. A. Tobagi and L. Kleinrock, “Packet Switching in Radio Channels: Part II—The Hidden Terminal Problem in Carrier Sense Multiple-access and the Busy-tone Solution,” IEEE Trans. Commun., Vol. COM-23, pp. 1417–1433, Dec. 1975.

[8] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), “Multi-band OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a,” 10. Nov. 2003.

[9] IEEE 802.11 Task Group "s" on ESS Mesh Networking, "IEEE P802.11 Wireless LANs Usage Models," P802.11-03/802r23, May 2004.