Decentrally Controlled Wireless Multi-hop Mesh Networks for High Quality Multi-media Communications

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ABSTRACT
Wireless mesh technology is receiving growing attention. Multi-hop operation can be implemented in high quality multi-media communication systems to achieve cost efficiency. However, hidden and exposed stations which commonly appear in mesh environments might remarkably deteriorate the network performance. Moreover, QoS requirements especially the delay requirement is a great challenge for delivering real time services by means of multi-hop operation. We present a link-layer protocol named Wireless Channel-oriented Ad-hoc Multi-hop Broadband, or W-CHAMB, which is able to perform multi-hop delivery of multi-media services in mesh networks. The W-CHAMB protocol is based on TDMA/TDD technology, operating in a fully distributed manner on a single frequency channel. Multi-hop forwarding might take place simultaneously in different time slots. The QoS of accepted traffic is well guaranteed by making use of the channel-oriented structure. The simulation results indicate that the W-CHAMB protocol can efficiently exploit the channel capacity for delivering various traffic flows under their QoS requirements in a multi-hop mesh network. The W-CHAMB protocol is a candidate link layer solution for Task Group s (Mesh WLAN) of IEEE Working Group 802.11.

Categories and Subject Descriptors
C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless Communication*; C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Network – *Access Schemes*.

General Terms
Algorithms, Design, Performance

Keywords
Mesh networks, ad-hoc networks, multi-hop operation, QoS, multi-media, medium access control, synchronization

1. INTRODUCTION
Driven by the current trends, there are growing demands for delivering multi-media services such as voice, video and interactive games with guaranteed Quality of Service (QoS). A high data transmission rate is necessary to support high quality multi-media transmission services. From the view of feasibility and availability, operation frequencies supporting high data rate services will be above 3 GHZ [1]. However, transmission on such bands suffers much more from propagation attenuation than on low bands and has a low obstacle penetration rate too. Therefore, the high transmitting power and more base stations are required for obtaining a reasonable radio coverage. Multi-hop forwarding, a key element of mesh networks, offers an efficient way to reduce the required transmitting power to a reasonable level by dividing a long transmission distance into several shorter ones and extend the radio coverage without using costly base stations. In this sense, multi-hop capability should be a mandatory property of a wireless multi-media communication system in order to achieve cost efficiency. A mesh network, by simply defined, is a network where stations in the network can forward traffic that is not intended for it. Besides aforementioned advantages, multi-hop operation also helps to increase the throughput for the systems that offer different Physical (PHY) modes and to promote the robustness of a wireless network.

Implementation of an efficient multi-hop functionality needs solutions offered by a link layer protocol to properly handle hidden and exposed stations [6] in a mesh network. The well known decentralized Media Access Control (MAC) scheme IEEE 802.11 Distributed Coordination Function (DCF) [2] cannot function well in multi-hop networks since it cannot inhibit both the hidden and exposed stations in multi-hop environments [6]. Centralized schemes like Hiperlan2 [4] and IEEE 802.11 Hybrid Coordination Function (HCF) [5] can handle hidden stations and exposed stations in a network well since a central controller knows and controls all the transmission details. But the excessive required control information for multi-hop operation leads to a significant reduction in transmission efficiency with the increase of forwarders. Transmission more than 2 hops in a centralized system incurs a large waste of bandwidth. It appears that a large scale mesh network can be constructed easily in a distributed manner than in a centralized manner.

Implementation of QoS in multi-hop operation is another tough issue. QoS requirements especially the delay metric is a great challenge for multi-hop operation. A high achievable network throughput not necessarily goes in hand with a low packet delay.

For decentralized schemes, how to provision the bandwidth for a specific traffic to guarantee its QoS while not waste the resource is not a trivial issue. IEEE 802.11e Enhanced Distributed Channel Access (EDCA) [5] gives a primary solution on single hop environments, but the reported results are not so encouraging [7].

Achieving a fair share of the bandwidth between end-to-end flows in a multi-hop network where exists the serious interference is important for forming a stable mesh network. Without a good fairness guarantee strategy, a mesh network might be broken down either by intentionally or unintentionally initiating a 'special' connection.

The W-CHAMB protocol [8],[9] is a fully distributed control protocol. It is based on Time Division Multiple Access (TDMA) technology. A network is formed in an ad-hoc manner, working on a single frequency channel. The operation of a network requires that stations are synchronized. Transmission takes place in periodic time slots called traffic channels. Busy-E-Signals, in-band busy tones [13], are used to inhibit hidden stations. The primary contributions of our paper are summarized as follows:

- We extend the prioritized access from two phases to three phases. Based on this change, we developed the synchronization algorithm and Fairness Algorithm (FA).
- We propose on demand Time Division Duplex (TDD) by making use of Busy-E-Signals used in Echo channel. The On-demand-TDD significantly improves the channel utilization when delivering asymmetric traffic flows like Voice over IP (VoIP) streams.
- We propose packet multiplexing technique based on the TDMA structure. This technique remarkably improves the throughput and delay performance for multi-hop transmissions.
- We develop a set of control algorithms for traffic channels to enhance the channel utilization by making the channel-oriented technology behave as the packet-oriented technology. The control algorithms include setting of hang-on time and valid transmission time for a specific traffic channel, and adaptation of the number of traffic channels for a link as the change of traffic load.
- We develop the W-CHAMB Radio Link Control (RLC) protocol for error control and flow control. We also adapt the RLC protocol to support multi-hop operation.

The rest of the paper is organized as follows: In Section 2, we discuss related work. Section 3 describes the W-CHAMB protocol. Section 4 uses an example to illustrate why the W-CHAMB protocol performs well in mesh networks. The performance evaluation results are presented in Section 5. We finally conclude in Section 6.

2. RELATED WORK

To the best of our knowledge, we are not aware of any reported work that performs a systematic study of the link layer protocol which is able to support high quality multi-media transmission services in decentrally controlled multi-hop networks. IEEE 802.11e EDCA is a distributed control protocol evolving from IEEE 802.11 DCF. It aims at providing QoS support for real-time services in single hop environments. IEEE 802.15.1 (Bluetooth) [12] and IEEE 802.15.3 [11] are two standardized Wireless Personal Area Networks (WPAN) protocols. IEEE 802.15.3 supports data rates of 20 Mbps or more, intended for high rate WPAN networks, while Bluetooth for wireless communication between portable devices with data rates up to 723.2 kbps. Both the high rate and Bluetooth WPAN networks operate in a centralized manner. Bluetooth systems implement multi-hop operation by forwarding data between multiple frequency channels. In order to implement multi-hop operation, a forwarding station in an IEEE 802.15.3 network must use the time slots allocated by the piconet coordinators (PNC) to transmit both data and control packets with the source and destination stations.

Lots of efforts have been put on constructing efficient multi-hop mesh networks. Most of those works are conducted by modifying the IEEE 802.11 DCF, and can be divided into 3 categories.

The first category is using multiple frequency channels. Dual Busy Tone Multiple Access (DBTMA) [13] divides a common channel into two sub-channels, one data channel and one control channel. Busy tones are transmitted on a separate control channel to inhibit hidden station, while data packets are transmitted on the data channel. Slotted Seeded Channel Hopping (SSCH) [14] is a link layer protocol which is able to increase the capacity of an IEEE 802.11 DCF network by utilizing frequency diversity. It runs over unmodified DCF MAC scheme. A pseudorandom sequence is used by a station to decide which channel to switch the interface to every time slot. Jungmin et al. [15] proposes a MAC protocol that utilizes multiple channels dynamically to improve the multi-hop performance.

The second category is to obtain the performance improvement by adapting the IEEE 802.11 DCF to support the directional and smart antenna technology [16] or other technologies like Code Division Multiple Access (CDMA) [17]. However more efforts should be made to make a wireless network operable in multi-hop environments by using those ideas.

The third category is to enhance the IEEE 802.11 DCF itself without using the multiple frequency channels or other new equipments. In Distributed Reservation Request Protocol (DRRP) [26], a transmission pairs inform their neighboring stations about the planned transmission when exchanging RTS/CTS packets. Potential hidden stations restrain their transmission according to received reservation requests.

3. THE W-CHAMB PROTOCOL

W-CHAMB is a link layer protocol for wireless broadband systems. It can work on a single frequency channel, independent of PHY schemes. The possible PHY layers include: IEEE802.11a/g PHY, Orthogonal Frequency Division Multiple Access (OFDMA), Multi Carrier Code Division Multiple Access (MC-CDMA), and other forthcoming high data rate transmission schemes.

Possible applications include the next generation WLAN and future WPAN systems. Due to the ability to quickly form a network in a fully distributed manner, the W-CHAMB protocol is also a candidate link layer solution for car-to-car communications and sensor networks.

3.1 Protocol Stack

Figure 1 describes the protocol stack of the W-CHAMB system. The W-CHAMB protocol consists of three parts. The W-CHAMB

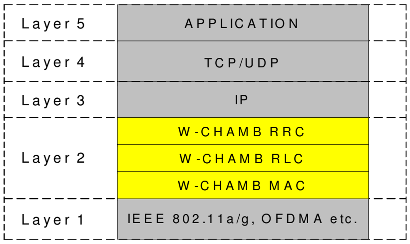


Figure 1. Protocol stack of the W-CHAMB system.

MAC protocol manages the access to the radio medium, the use of the TDMA channels, handling of hidden and exposed 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 contains Call Admission Control (CAC) for QoS support and wireless resource related management algorithms.

3.2 The W-CHAMB MAC Protocol

3.2.1 MAC Frame and Energy Signals

The MAC frame and waveform of energy signals are shown in Figure 2a. Energy signals, in-band busy tones [13], 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).

W-CHAMB is a distributed TDMA/TDD system. It requires that stations in a network are synchronized. A solution for synchronization is given in [10]. 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 AESes 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 different with different PHY schemes and applications. All the MAC frame related parameters are never changed during operation. Unless otherwise stated, all the time parameters shown in this paper assume the IEEE 802.11a PHY and WLAN application.

3.2.2 Prioritized Access

An ACH slot has three phases: the Prioritization, Contention and Transmission phase as shown in Figure 2b. A number of binary

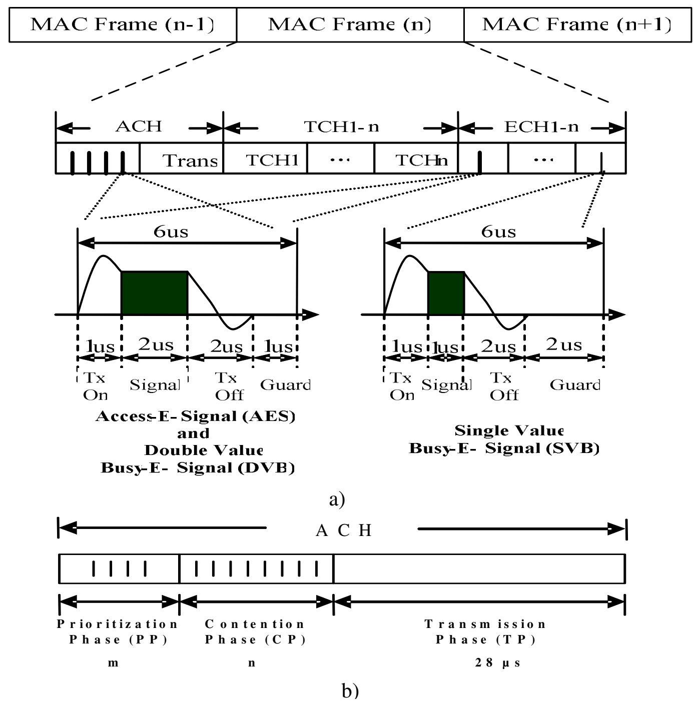


Figure 2. a) MAC frame and waveforms of energy signals; b) ACH structure.

AESes are used in the first two phases to implement a prioritized access mechanism. The Prioritization phase is the QoS related contention phase. The setting of the Contention phase is to guarantee with a high probability that there is only one winner under a heavy contention. Assume that the number of binary AESes in the Prioritization and Contention phases of an ACH is m and n, respectively. The number m is associated with the QoS level, 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 either 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 in the Prioritization phase. 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 the Prioritization Phase use the same listening and sending scheme again to contend in the Contention Phase by a number from $[0, 2^n-1]$.

5) The final winner of the previous phases then sends out a packet in the Transmission Phase.

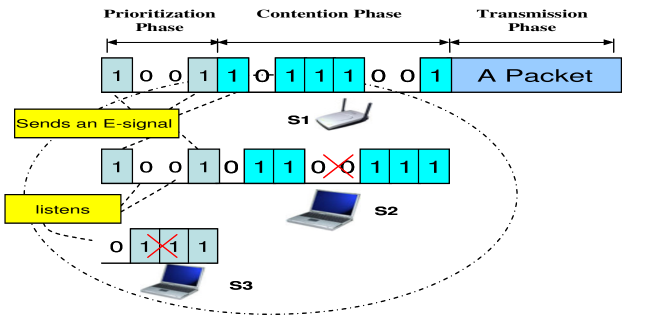


Figure 3. An example of contending for an access. Stations S1, S2 and S3 are in the transmission range of one another.

Figure 3 illustrates a contention process. The stations S1, S2 and S3 are in the transmission range of one another. They happen to enter in the contention process at the same time. S1 and S2 want to set up a one hop VoIP connection with their partners, while S3 wants to initiate a one hop video stream connection. Assume that the QoS priorities of the VoIP and video stream are 9 (1001) and 7 (0111) respectively. Both S1 and S2 win in the first phase contention by means of listening and sending AESes. After that, each of them randomly generates a number and uses the number to compete again in the second phase. As shown in Figure 3, the generated numbers of S1 and S2 for the second phase are 185 (10111001) and 103 (01100111) respectively. S2 quits the second phase contention immediately since it hears an AES at the beginning of the phase. Finally, S1 gets the right to send out a request packet in the Transmission Phase.

3.2.3 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, the one hop connection ID, QoS-related traffic specification (QTS) and a list of proposed TCH slots in the Transmission slot of the 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.

3.2.4 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

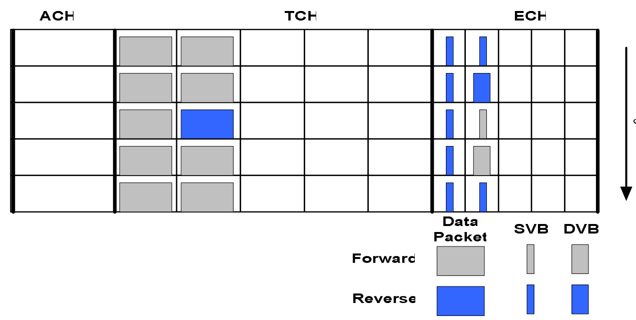


Figure 4. An example of transmission and On-demand-TDD.

TCH(s). This scheme is called On-Demand-TDD. Figure 4 shows an example of the process.

The decision whether to transmit a DVB to apply for the reverse transmission direction of a TCH is made according to the transmit buffer length in the receiving station and the arrival rate of up-coming packets. If necessary, a station in the connection attempts to gain more TCH(s) in order to be able to meet the QoS requirement by competing with adjacent stations.

3.2.5 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. A multi-hop connection consists of multiple one-hop connections in tandem that each is independently controlled.

3.2.6 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.

When there is no packet for transmission in a TCH, the involved stations would not release the TCH immediately. Instead, they may keep the TCH for a certain period (hang-on time), to wait for the arrival of new packets from the up-layer or from nearby stations to be forwarded on the TCH. The newly arrived packets during the hang-on period are also transmitted via the TCH, and this cause a reset of the hang-on time at both sides. Otherwise, after the expiration of the hang-on time, a reserved TCH would be freed (No packet in TCH and No SVB in ECH).

A TCH in hang-on status avoids high priority flows that must contend for reserving TCH(s). A longer hang-on time might also lead to the waste of capacity. Therefore a trade-off must be made. In W-CHAMB networks, a TCH in hang-on status is immediately assigned to any urgent request to establish a one hop connection, if no free TCHs are available.

The hang-on time for a TCH is set according to the QoS level of flows. The higher the QoS level, the longer the duration. Some example values can be found in the simulation parameter setting.

3.2.7 Valid Transmission Time (VTT):

Several long-lived flows like File Transmission Protocol (FTP) traffic and video stream might cause a network to be in a saturated state. When this happens, stations cannot obtain a transmission chance even if they might have higher QoS traffic like VoIP to transmit.

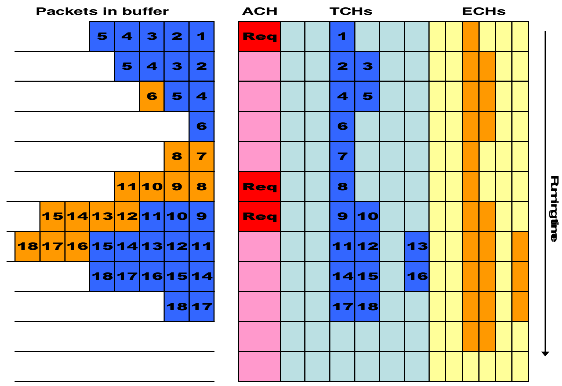


Figure 5. Dynamic adjustment of TCH number for a one hop connection. The hang-on time of the connection is 1 MAC frame; the maximum allowed TCH number is 3 (by QoS).

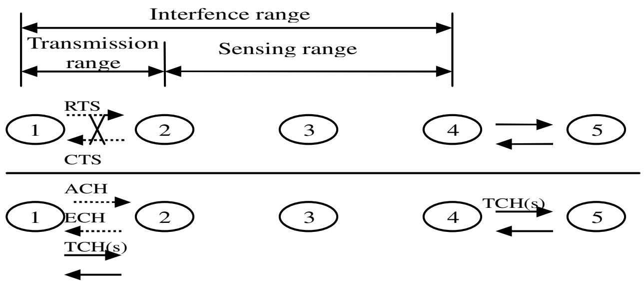


Figure 6. An example of transmission in multi-hop networks. Station 1 wants to setup a connection with 2 while a transmission is ongoing between stations 4 and 5.

To prevent an excessive use of a TCH, each TCH is associated with a VTT value according to the traffic type. Generally speaking, a higher QoS traffic is assigned with a long VTT value. A station is forced to release a reserved TCH after the expiration of VTT. It would compete for a TCH again if necessary. With this feature, the W-CHAMB has a property of statistical interruption, which is in favor of high QoS traffic.

3.2.8 Adaptation of TCH Number for A One Hop Connection

1) A station shall contend for one more TCH if the current TCH(s) cannot satisfy the traffic needs. As aforementioned, the allowed maximum number of TCH(s) for a one hop connection is associated with the type of traffic.
2) A TCH would be released after the hang-on time or VTT.

Figure 5 illustrates how the W-CHAMB protocol handle a highly bursty real-time service like video streams in an efficient way, satisfying the transmission needs while not wasting the time slots.

3.2.9 Fair Algorithm (FA)

Fairness is very important for a wireless mesh network. The IEEE 802.11 DCF performs badly in multi-hop networks not only in terms of throughput but also fairness [6].

The Contention phase in the ACH is used to ensure that there is only one winner to transmit in the Transmission phase. Assume an AES has a duration of 6 µs and the number of AES in Contention phase is n. By introducing an overhead of 6*n (µs), the amount of the different contention levels is up to 2^n. When a station contends with others for sending a TCH reservation request, the contention number used for the second phase in the ACH is generated according to the number of lost contention for sending the request. The more a station loses the contention to send the request, the higher probability for it to obtain a bigger contention number.

3.2.10 Synchronization

The design of a synchronization scheme for a distributed TDMA system aiming at high speed communication is really a challenging work. Rui et. al. [10] gives a primary solution for W-CHAMB networks. We developed an enhanced scheme and will present it in our later publication.

3.3 The W-CHAMB RLC Protocol

The RLC protocol offers data transfer service to the upper layer. It fragments the data packets from the higher layer into appropriate RLC Protocol data units (PDUs) and passes them to the MAC layer. The length of RLC PDUs depends on the PHY mode. There are two kind modes of service: UM for connectionless point-to-point, multicast and broadcast applications, AM for reliable point-to-point transmissions. A selective repeat ARQ (SR-ARQ), by taking advantage of the On-demand-TDD feature in the MAC, is designed as the link layer error and flow control scheme for AM [9].

In order to support multi-hop operation, a station often needs to maintain several ARQ entities with different ARQ parameters in parallel in its RLC entity.

4. WHY THE W-CHAMB PROTOCOL PERFORMS MULTI-HOP OPERATION WELL?

In this Section, a string topology shown in Figure 6 is used to illustrate why the W-CHAMB protocol performs multi-hop operation well. Each station in the topology can only transmit with its direct neighbor(s). The sensing, interference and spatial reuse distance are 2, 3 and 4 hops away, respectively. Station 1 wants to send data to 2 at a moment that a transmission is ongoing between stations 4 and 5. In this situation, the station 1 has no idea about the ongoing transmission, but station 2 does.

In the IEEE 802.11 DCF network (the upper part), the exchanges of RTS-CTS handshake between station 1 and 2 are corrupted by station 4 since station 1 and 4 do not know the existence with each other. The transmitting of either would cause the interference with another. At the case, station 4 and 1 are a hidden station pair. While in the W-CHAMB network (the lower part), the situation is different. Station 1 shall contend in the ACH to send a TCH reservation request with a list of proposed TCH(s) observed at its own place. This transmission will not be interfered by the ongoing transmission because the ACH and TCH(s) appear in the different time slots. After receiving this request, station 2 shall select TCH(s) from the proposed list based on its own channel knowledge at its location. Since it knows the ongoing transmission, it would choose TCH(s) not being used by station 4 and 5. Then it notifies station 1 of the accepted TCH (s) by transmitting a SVB in corresponding ECH(s). Later on, two transmissions take place in parallel in a MAC frame in different TCH slots. The proper handling of hidden and exposed stations leads to an efficient multi-hop operation of W-CHAMB networks.

Modulation	Bit rate [Mbps]	Bytes per TCH	Minimum sensitivity at receiver (dbm)
BPSK ½	6	27	-85
BPSK ¾	9	40.5	-83
QPSK ½	12	54	-81
QPSK ¾	18	81	-79
16QAM ½	24	108	-75
16QAM ¾	36	162	-73
64QAM ¾	54	243	-68

Table 1. Key parameters for different PHY modes.

Parameter settings in the MAC frame	
Energy signals in Prioritization phase (ACH)	4
Energy signals in Contention phase (ACH)	8
Duration of the transmission phase in an ACH	28 µs
Duration of a TCH	45 µs
Duration of an ECH	6 µs
TCHs/ECHs in a MAC frame	16
Length of a MAC frame	916 µs

Table 2. Parameter settings in a MAC frame.

ACH contention ranges can be tuned to be larger than data transmission ranges. Suppose at one moment, station 1 wants to initiate a connection with 2 while 5 wants to initiate one with 4. Since station 1 and 5 can sense AESes from the other, they would contend with each other in the ACH. Finally, the winner gets the chance to set up a connection first. Otherwise if two connections are set up simultaneously and they happen to select same TCH(s), the later transmissions will interfere with each other.

5. PEROFRMANCE EVALUATION

We design two simulation scenarios to reveal the overall performance of the W-CHAMB system. The metrics used to evaluate the performance include throughput, fairness, packet delay, packet loss rate (PLR). PLR is the ratio of the amount of lost packets to the amount of sent packets at the sender in a given duration. The fairness is calculated by using Jain's fairness index given in [19].

5.1 Simulation Tool

To evaluate the performance of the W-CHAMB protocol, an event-driven simulator is developed in C++.

5.1.1 Channel Model

The Multi-Wall-and-Floor Model [20] is adopted as path loss Model. The received power P_R in dBm is computed by:

$$P_R = P_T - L_{MWF} + G \quad (1)$$

Where P_T is the transmitted power; L_{MWF} is path loss between the sender and receiver; G is the amount of receiving and transmitting antenna gains. It is assumed that the omni directional antennas are used and the antenna gain is 6 dBi.

Traffic	Load (kbps)	APDU Size (bytes)	Max Delay (ms)	Max PLR
VoIP	22.4	100	60	6%
Video conference	Mean:256 Max:1280	500	100	0.1%
WWW	-	Mean:480 Max:66666	-	0
CBR	Variable	500	-	-

Table 3. Traffic loads and their QoS requirements

Different from data packets, when contending in the ACH, Energy signals help with each other to be sensed. The signal-to-interference-and-noise (SINR) values of energy signals and data packets are calculated by Eq. 2.

$$SINR = \begin{cases} \dfrac{C + \sum I}{N} & \text{for Energy signals} \\ \dfrac{C}{\sum I + N} & \text{for Data PDUs} \end{cases} \quad (2)$$

5.1.2 Physical Layer

The PHY layer assumes the OFDM-based IEEE 802.11a PHY working at 5.2 GHZ. Packet error ratios (PERs) are calculated by the relation between SINR and PER reported in [21]. A TCH slot is fit by 9 OFDM symbols. Table 1 shows the packet lengths per TCH and the minimum sensitivity levels of a receiver for each modulation scheme [3]. In the simulator, a data packet may be decoded only if the received SINR value is over than the minimal sensitivity level. Receive noise floor is assumed as -93 dBm.

5.1.3 MAC, RLC, IP and Transport Layers

All the introduced features of the W-CHAMB protocol have been implemented in the simulator. Table 2 describes the MAC frame parameters for the evaluation work by assuming the WLAN application and IEEE 802.11a PHY.

For simplicity, we use the pre-specified route strategy instead of using wireless routing protocols in the IP layer. User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) (version: Reno) are implemented in the Transport layer.

5.1.4 Application Layer

Four types of traffic sources are used: VoIP, video conference and WWW, constant bit rate (CBR). The description of traffic sources and their QoS requirements is presented in Table 3. Important configurations in the Transport, RLC and MAC layer for each service are shown in Table 4.

A VoIP source (G. 711 coder) is modeled by the two-state on-off model with exponentially distributed duration of voice spurts and silent gaps. A VoIP source generates data with a mean bit rate of 22.4 kbps. The maximum packet loss rate (PLR) should be lower than 6% in order to preserve voice quality. The QoS priority of a VoIP MAC PDU is 9.

The on-off minisources [22] model is used to generate high bit rate video conference (H. 263 codec) streams. The mean and highest bit rates of a video conference source are 256 kps and 1.28

Traffic	Transport protocol	RLC	MAC		
			Priority	HangOn	VTT
VoIP	UDP	UM	9	8	300
Video conference	UDP	SR-ARQ	7	6	200
WWW	TCP	SR-ARQ	2	4	100
CBR	UDP/TCP	UM/AM	6	4	100

Table 4. Important configurations for various services (units for HangOn and VTT: MAC frames)

Mbps, respectively. The maximum tolerable delay and PLR for video conference traffic are 100 ms and 0.1% respectively.

As another highly bursty traffic flow, WWW is simulated by the model specified in [23]. A WWW source produces packet streams with a mean PDU length of 480 byte, while the longest PDU length reaching 66666 byte as shown in Table 3. The WWW traffic has no delay requirement, but it requires zero PLR.

For real-time traffic, in case the delay of a MAC PDU exceeds the maximum tolerable delay, the packet is dropped.

The CBR traffic is a simple way to simulate additional traffic services. Its generated load and configurations at lower layers are variable with the simulated task.

According to the QoS requirements, different combinations of transport and RLC control protocol should be used for different services. As shown in Table 4. The VoIP traffic needs UDP/UM, while the video conference and WWW traffic require UDP/SR-ARQ and TCP/SR-ARQ, respectively.

5.2 Simulation Results

It is assumed that the W-CHAMB protocol runs on the IEEE 802.11a PHY at 5.2 GHZ. In all the scenarios, the transmit power from a station is 100 mW. 16QAM 1/2 (24 Mbps) and QPSK 1/2 (12 Mbps) are selected as the PHY modulation schemes for transmitting data and Beacon packets, respectively. The transmission ranges of data and Beacon packets from a station are therefore approximately 100 and 180 meters, respectively.

5.2.1 Traffic Performance in Single Hop Networks

60 stations are randomly placed in a square of 100 meters × 100 meters. All stations are within transmission range of each other. Every source station can transmit to its destination in one hop. Each transmission pair is randomly selected and a station at most generates one data flow. The basic traffic performance is studied by comparing with the results from the 802.11 DCF in comparable configurations. We use CBR sources, each of which sends a packet every 2 ms. UDP/UM are selected as the transport protocol and the RLC mode. We also confine that the maximum number of TCH for a flow is 2. The packet length of UDP packets are 512 bytes. As shown in Table 1, the length of the W-CHAMB MAC PDUs is 108 bytes when the PHY mode is 16QAM 1/2. While for the comparable the 802.11 DCF, the maximum length of MAC PDUs is set as 600 bytes.

Figure 7 shows the aggregated throughput with the increase of flows. It can be seen that when the number of flows is less than 5, the amount throughput from the W-CHAMB network is almost

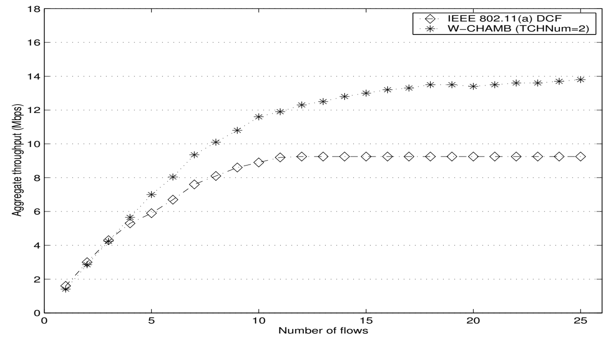


Figure 7. Aggregate throughput with increasing of flows.

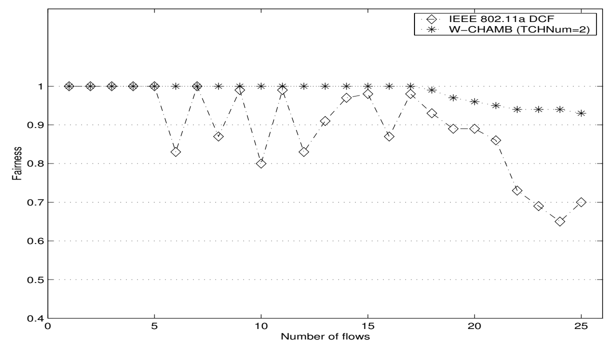
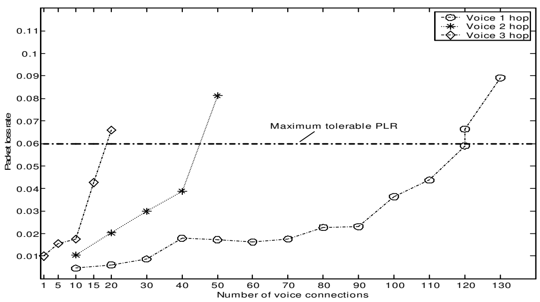


Figure 8. Fairness with increasing of flows.

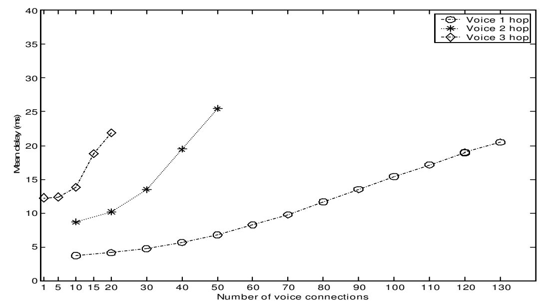
same as that from the 802.11 DCF network. While when the number of flows increases, the aggregated throughput of the W-CHAMB network increases more quickly than that of the 802.11 DCF network. Meanwhile, the 802.11 DCF network gets into the saturated state much earlier than the W-CHAMB network. When the number of flows is 25, the W-CHAMB network obtains 14 Mbps overall network throughput, which is 35% higher than the value achieved in the 802.11 DCF network (9.5 Mbps).

Three reasons lead to those differences. Firstly, the 802.11 DCF achieves high efficiencies only with long MAC PDUs. With a not short length of 600 bytes, the control overhead of DCF is still too much. On the contrary, the W-CHAMB protocol achieves a high efficiency when transmitting shorter MAC PDUs. Secondly, a longer MAC PDU results in a higher PER. Suppose that the PER of a W-CHAMB MAC PDU (108 byte) is A, it can be derived that the PER of an 802.11 MAC PDU (600 bytes) is $1-(1-A)^{600/108}$. As an example, when A is 1%, the PER of an 802.11 MAC PDU is 5.4%. Thirdly, the W-CHAMB protocol performs well in a highly loaded situation. While the 802.11 DCF get stations more frequently into the back-off state.

Figure 8 exhibits the fairness performance. The W-CHAMB protocol distributes bandwidth fairly between flows. The fairness index stays within 0.90 even when the flow number is 25. This achievement is attributed to FA and control algorithms such as the hang-on time and VTT. By contrast, the fairness index in the 802.11 DCF network oscillates even when the number of flows changes a little bit. As a steady trend in the 802.11 DCF network, the fairness goes down as the increasing of flows. In fact, the W-CHAMB protocol performs fairness much better than 802.11 DCF in multi-hop scenarios since the W-CHAMB protocol can handle hidden stations well while the 802.11 DCF cannot. We will exhibit those results in our later publications.

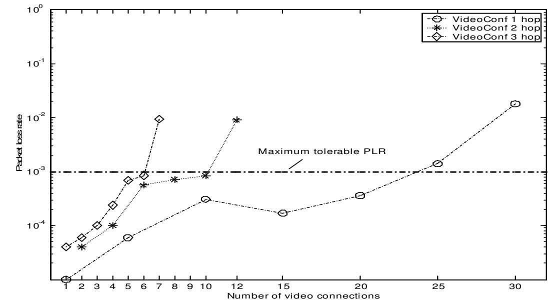


a)

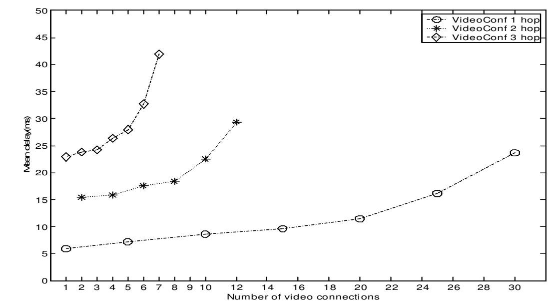


b)

Figure 9. a) PLR with VoIP connection; b) Mean end-to-end delay with VoIP connection;



a)



b)

Figure 10. a) PLR with video conference connection; b) Mean end-to-end delay with video conference connection.

5.2.2 QoS Performance in Multi-hop Operation

200 stations are placed in a square of 690 meters x 690 meters. An AP is in the centre of the square. It is assumed that all the end-to-end connections are established between the AP and a mobile station. A source station except AP generates at most one flow at a time. The AP is a bottleneck station in this study. Packets from the farthest stations need 3 hops to reach the AP.

The delay requirement of real-time services is a great challenge for multi-hop operation. A multi-hop connection needs several one hop connections established to forward packet flows. Therefore, a multi-hop connection of n hops produces an n time higher overall network traffic load than a one hop connection. Moreover, hop-by-hop forwarding adds queue delays at each intermediate station to the overall end-to-end delay when it attempts to establish a one hop connection with its next destination.

The first study of interest is to investigate the number of real-time traffic connections which can be served simultaneously in a scenario, which is homogenous concerning number of hops per connection and traffic type. As plotted in Figure 9a, the studied network is able to support up to 120 simultaneous single hop VoIP connections with the PLR less than 6%. As stated, hop-by-hop forwarding in a W-CHAMB multi-hop connection is able to achieve low end-to-end packet delays. Therefore, the number of simultaneous VoIP connections with either 2 or 3 hops still reaches to 45 and 12, respectively, under the PLR requirement. The corresponding end-to-end delay performance is exhibited in Figure 9b. For one hop VoIP connection, the average end-to-end delays increase slightly with the number of connections. When 120 concurrent connections are established, the average end-to-end delay is around 24 ms. In comparison, the end-to-end delays increase sharply with the connection number in the simulation runs for 2 and 3 hop connections, as shown in Figure 9b.

A Video conference source generates highly bursty traffic. In a wireless broadband system, how to allocate bandwidth efficiently for video traffic flows is very important for achieving high resource utilization, and at the same time meeting the QoS requirements. Assumed that the tolerable PLR is 0.1%, the number of simultaneous one hop video conference connections supported by the studied network is around 24, as indicated in Figure 10a. With the information from Table 3, it is calculated that the overall amounts of mean and highest bit rate of 24 video sources are 6.144 Mbps and 30.72 Mbps. The result is very encouraging since it is achieved on a PHY layer with a data rate of 24 Mbps. It implies that the algorithm used to dynamically adjust the TCH number for one hop connections works well. Figure 10a also indicates that the supported numbers of 2 and 3 hop video connections under the given PLRs are 10 and 6, respectively. The end-to-end delay performance is shown in Figure 10b. The trend is quite similar to that in Figure 9b with the increase of hops.

The second study is conduced to reveal the QoS performance of W-CHAMB networks with mixed traffic services. In this study, 6 one hop and 6 two hop VoIP connections, 3 one hop and 3 two hop video conference connections, and additionally, 12 one hop and 12 two hop WWW connections are initiated simultaneously. The above traffic flows are grouped in 6 groups. The flows generated from the same kind of traffic sources with the same number of hops constitute one group. The Complementary Distribution Function (CDF) of the end-to-end delay for each group is shown in Figure 11. For same number of hops, VoIP and video conference flows achieve lowest and second lowest end-to-end delay since traffic type related MAC parameters are set in favor of the real-time traffic as shown in Table 4. And for the same traffic type, the end-to-end delay of the one hop connections is almost 2 times lower than that of the two hop connections. The additional queue delay at the intimidate station for multi-hop

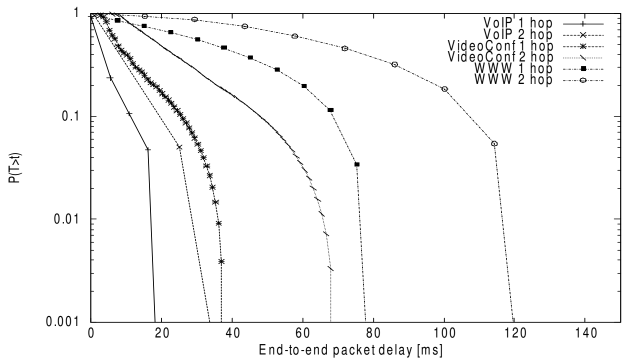


Figure 11. CDF of mean end-to-end delays for different traffic groups. 6 one hop VoIP , 6 two hop VoIP, 3 one hop video, 3 two hop video, 12 one hop WWW and 12 two hop WWW connections are run simultaneously.

forwarding leads to this difference. The two hop WWW connections experience the highest end-to-end delays. However, most of the values are lower than 100 ms (80%). It can be deduced that the multi-hop network with the overall amount of 42 mixed end-to-end traffic flows is able to serve flows in parallel, meeting the particular QoS requirements. The QoS mechanisms of the W-CHAMB protocol works efficiently in multi-hop networks.

6. CONCLUSIONS

W-CHAMB is a TDMA/TDD based wireless broadband system, operating in a fully distributed manner on a single frequency channel. It is able to implement an advanced QoS support in multi-hop networks. The possible PHY layers are: IEEE802.11 a/g PHY, OFDMA, MC-CDMA and forthcoming high data rate transmission schemes.

The multi-hop and QoS performance of the W-CHAMB mesh network is investigated by the simulative approach. The simulation results show that the bandwidth can be fairly shared between end-to-end flows even in heavily loaded situations. The W-CHAMB protocol has a good capability to handle multiple distinct traffic flows and types in parallel, meeting the particular QoS requirements in multi-hop operation, while achieving the high channel utilization. In future, we will investigate the ways of integrating the W-CHAMB protocol with DCF/EDCA to construct 802.11 Extended Service Set (ESS) [2] mesh networks.

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