Constructing Efficient Multi-hop Mesh Networks

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Abstract

The Wireless Channel-oriented Ad-hoc Multi-hop Broadband (W-CHAMB) is a new link layer protocol with the aim of being able to support Quality of Service (QoS) in multi-hop operation in fully distributed ad hoc networks. It is based on Time Division Multiple Access (TDMA) technology, operating on a single frequency channel. In this paper, we improve the prioritized access mechanism by inserting the Contention Phase (CP) into the access slot. Then we propose 3 new algorithms to enhance the traffic performance in the multi-hop environment: On demand Time Division Duplex (On-demand-TDD) for achieving high channel utilization; Fairness Algorithm (FA) for acquiring the fairness even in a highly interfered multi-hop network; Setting Valid Transmission Time (VTT) for each traffic channel to prevent an excessive use of the traffic channel. The extensive simulations are performed by evaluating Transmission Control Protocol (TCP) performance over W-CHAMB multi-hop networks under heavy load situations. The achievable TCP throughput, packet delay, fairness and stability have been investigated. Results exhibit the outstanding multi-hop performance of the W-CHAMB protocol.

1. Introduction

Multi-hop operation, the key issue to form a wireless ad hoc mesh network, has been a research topic in the mobile computing community for a long time. In addition to be able to extend the transmission range, multi-hop operation also helps to increase the throughput in a multi-Physical (PHY) modes environment. It may implement high data rate transmissions at reasonable power consumption and promote the robustness of an ad-hoc wireless network. Currently, designing good Media Access Control (MAC) protocols, which are able to calm down both hidden station and exposed station in a multi-hop environment, is the real key issue that might lead to the success of the multi-hop concept.

As the well-known decentralized scheme, the IEEE802.11 Distributed Coordination Function (DCF) has been assumed as the default MAC scheme for studying multi-hop networks for a long time by numerous researchers. However lots of simulative [7, 8] and testbed results [9] point out that the DCF cannot be used to form an efficient multi-hop network since the formed network suffer both the hidden and exposed station problems.

The W-CHAMB protocol [3-5] is also a decentralized protocol. A network is formed in the ad-hoc manner. It is able to support multi-hop operation with QoS guarantee. The W-CHAMB protocol is based on TDMA technology. Transmission takes place in periodic time slots. Energy signals, in-band busy tones [10], are used to inhibit hidden and exposed stations in a multi-hop environment. Owing to the TDMA structure, a multi-hop forwarding might take place simultaneously in different traffic channels, achieving low end-to-end packet delays.

However, the previous access mechanism cannot efficiently handle a highly contending scenario, which case however appears frequently in a multi-hop network. When the case happens, instead of obtaining traffic channels in time, a node may get into the back-off status quite often. Lots of traffic flows require the involved stations to exchange information during transmission. How to efficiently allocate traffic channels in this case is a challenge issue in a channel oriented system. Achieving a fair share of bandwidth between end-to-end flows in a multi-hop network is another important issue. Without a good fairness implementation, a network might be broken down either by intentionally or unintentionally initiating a ‘special’ connection. A long-time holding of traffic channels by lower level massive traffic flows might lead that higher QoS flows cannot obtain a transmission chance in a long time. This paper presents the solutions for all above mentioned problems.

TCP is one of the prevalent transmission applications in the IP world, offering reliable in-sequence data transfer to the upper layer. It adapts to the network condition and performs congestion control. The traffic performance of TCP is very sensitive to a system behavior. In this article, TCP performance over W-CHAMB multi-hop networks is investigated over string and grid topologies.

The rest of the paper is organized as follows: the new version of the W-CHAMB protocol is described in Section 2. In Section 3, an example is used to illustrate why the W-CHAMB protocol perform well in multi-hop networks. Section 4 exhibits the simulation results of TCP performance over W-CHAMB multi-hop networks. The conclusion is drawn in Section 5.

2. W-CHAMB

Possible PHY schemes of the W-CHAMB system include IEEE 802.11a/g, and forthcoming high data rate transmission schemes. Potential applications include future Wireless LANs (WLAN), Wireless personal networks (WPAN) and sensor networks. All the parameters appeared in this paper assume the IEEE 802.11a PHY layer [1] and WLAN application.

2.1. Protocol stack

Fig. 1 describes the protocol stack of the W-CHAMB system. The W-CHAMB MAC protocol manages the access to the radio medium, the use of the TDMA channels and implementation of synchronization. The W-CHAMB Radio Link Control (RLC) protocol provides data transfer service to the upper layer in the acknowledge mode (AM) and unacknowledged mode (UM). The Automatic Repeat Request (ARQ) is the key component of the AM. The W-CHAMB Radio Resource Control (RRC) protocol takes care of wireless resource related algorithms like Call Admission Control (CAC), power control and dynamic frequency selection.

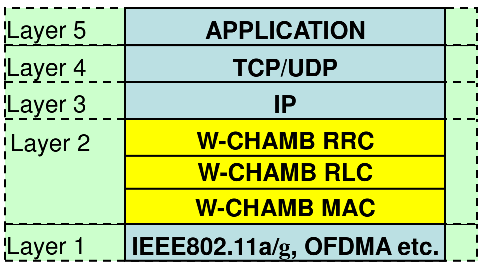

Figure 1: Protocol stack of W-CHAMB.

2.2. MAC frame and energy signals

The MAC frame and waveform of energy signals are shown in Fig. 2a. Energy signals, in-band busy tones [10], play important roles in W-CHAMB. An energy signal occupies a short time slice, saying a period of 6 µs. Energy signals can be classed into two types: Access-E-Signal (AES) and Busy-E-Signal (BES).

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 number of traffic channels, length of a MAC frame and the number of energy signals should adapt with PHY choices and applications. All the MAC frame related parameters are never changed during operation.

2.3. 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

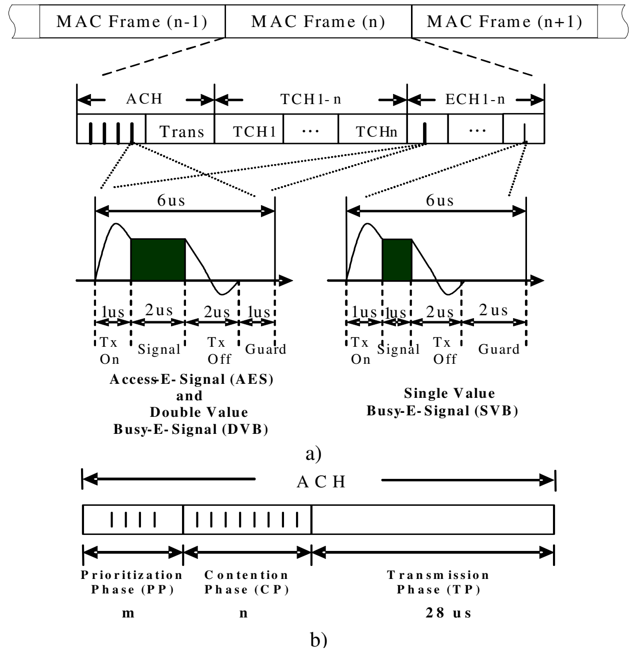

Figure 2: a) MAC frame and waveforms of energy signals; b) ACH structure.

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 in each 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 $[0, 2^n\text{-}1]$.
5) The final winner of the previous phases then sends out a packet in the TP.

2.4. 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. In a multi-PHY modes environment, Access-E-Signals are transmitted with a higher transmission power, which helps that an ACH contention takes place in a much larger area than data packet transmission ranges. This setting prevents two connections whose involved stations in the sensible range of each other from being set up simultaneously.

2.5. Transmission and on-demand-TDD

Once TCH(s) have been reserved for a connection, an originator uses one or some of them to send out its data packets and no matter whether the receiver correctly receives the packets or not, it will reply with the SVB(s) in the related ECH(s) to signal the occupancy of the respective TCH(s). In case the receiver has some data to send back, it transmits a DVB instead of a SVB on the related ECH(s). 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 sends out packets via the reserved TCH(s). This scheme is called On-Demand-TDD. Fig. 3 shows an example of this process.

Whether a receiver applies for the alternative transmission chance is made according to its buffer length and arrival rate of packets for delivery. If necessary, either side in a transmission will contend to reserve more TCH(s) for use under the QoS constrain of the transmission. A set of algorithms are developed for making the decision and also for making the On-demand-TDD stable in case of loss of either a packet or SVB. The more detailed algorithm will be presented in a special paper.

With the On-demand-TDD, the TDMA based W-CHAMB achieves a high channel utilization when handling mutual traffic like Voice over IP (VoIP) and TCP flows.

2.6. TCH release and packet multiplexing

A hang-on time is used system wide to protect a reserved TCH against a too early release. A TCH established between adjacent nodes is used to multiplex any packets transmitting on the route. The sequence of transmitting packets on a TCH is determined according to the QoS priorities of packets.

2.7. Valid transmission time (VTT)

The channel-oriented structure helps the W-CHAMB protocol perform well in multi-hop mesh networks. However when there are several long lived traffic flows like File Transmission Protocol (FTP) massive flows or video streams in an area, nearby nodes cannot obtain a transmission opportunity even they might have higher QoS traffic like VoIP flows. In the case, a lot of data packets would be dropped even before transmitting since the delays of packets already breaks

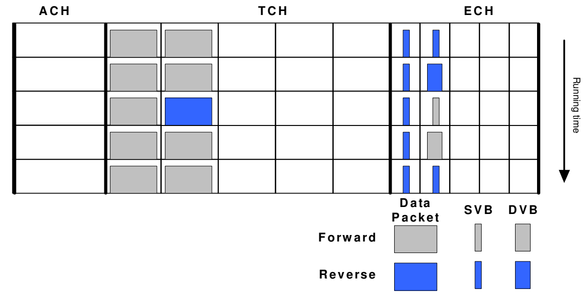

Figure 3: An example of transmission process and On-demand-TDD.

their QoS requirements.

To prevent an excessive use of a TCH, the VTT concept is put forward. Each TCH is associated with a VTT value according to the QoS type of a connection. Generally speaking, a TCH being used to carry a higher QoS traffic is assigned with a longer VTT value. A node is forced to release a reserved TCH on expiration of VTT. It attempts to contend in the ACH to gain a TCH later after experiencing a back off stage. With this change, the W-CHAMB protocol has a feature of statistical interruption, assisting high QoS traffic flows in winning more transmission opportunities. Due to the limited space, the in-depth discussion cannot be presented here. This paper will study the impact of the VTT value on TCP performance in multi-hop networks.

2.8. Fairness algorithm (FA)

The fairness is very important for a wireless ad-hoc network. The decentralized scheme DCF performs badly over multi-hop networks not only in the aspect of throughput but also fairness [7].

The CP phase in the ACH is used to ensure that there is only one winner to transmit in the TP phase. Assume an Access-E-Signal has a duration of 6 μs and the number of Access-E-Signals in CP 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 in the CP phase is generated according to the counted number of losing contention for sending the request. The more a station loses the contention to send a request, the higher probability for it to obtain a bigger contention number. Inside a station, a request for a higher level traffic and for forwarding will be handled firstly. The loser will get into a very short back off stage.

2.9. W-CHAMB RLC

The W-CHAMB RLC offers data transfer service to the upper layer. There are two 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.

TCP is designed for wired networks on the assumption that packet losses are almost solely owing to the network congestion. The use of TCP on the lossy wireless medium is only applicable either by modifying TCP itself or being assisted by the error control scheme in the link layer. In the W-CHAMB system, the SR-ARQ is used to help TCP work efficiently in wireless networks. The SR-ARQ combats the packet losses over radio by retransmitting RLC protocol data packets if necessary. It seems to TCP that there is no packet loss as long as no overflow happens in the RLC buffer.

In order to support multi-hop operation, a node often needs to maintain several ARQ entities with different ARQ parameters in parallel. Therefore, how to control the overall buffer consumption while providing sufficient support for each transmission is an important topic.

2.10. Synchronization

[6] gives a primary solution. 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 participants in Beacon generation. 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 a station determine whether it is located in "right" places. If so, it will send out Beacons more frequently. The synchronization accuracy is improved a lot as well.

3. Why the W-CHAMB protocol performs well in multi-hop networks?

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

In a DCF network, the exchanges of RTS-CTS handshake between node 1 and 2 are corrupted by node 4 since node 1 and 4 do not know the existence with each other. The transmitting of either would cause interference with another. At the case, node 4 and 1 are hidden station pair. While in a W-CHAMB network, the situation is different. Node 1 would contend in the ACH slot 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, node 2 would 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) other than the being used TCH(s) by node 4 and 5. Then it notifies node 1 of the accepted TCH (s) by transmitting SVB(s) in the corresponding ECH(s). Later on, two transmissions are taking place in parallel in the different TCH slots.

As pointed out in § 2.4, ACH contention ranges are

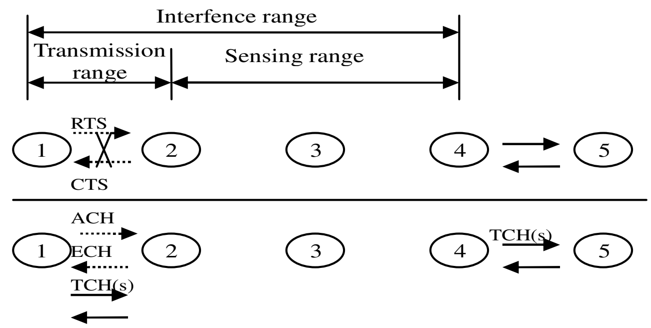

Figure 4: An example of transmission in multi-hop networks. Node 1 wants to setup a connection with node 2 while a transmission is ongoing between nodes 4 and 5.

tuned to be larger than data transmission ranges. Suppose at one moment, node 1 wants to initiate a connection with node 2 while node 5 with node 4. Since both node 1 and 5 can sense the Access-E-Signals 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.

4. TCP performance over W-CHAMB

4.1. Simulation environment

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

Channel Model

The Multi-Wall-and-Floor Model [11] is adopted as path loss Model. The received power in dbm is:

$$P_R = P_T - L + G \qquad (1)$$

P_T and P_R are transmitting and receiving power respectively; L is the path loss; G is the amount of antenna gain from receiving and transmitting. 6 dbi is used here as the antenna gain of omni directional antennas.

Physical Layer

The OFDM-based IEEE 802.11a is implemented in the physical layer. Packet error rates (PER) are calculated according to the relation between signal-noise-ratio SNR and PER reported in [12]. The transceiver related parameters are from published OFDM-related standards [1]. A data packet or an energy signal is possible to be decoded only if the received SNR value is over than the minimal receiver sensitivity. Receive noise floor is assumed as -93 dBm.

Different from data packets, when contending in the ACH, Energy signals help with each other to be detected. Assume that N, C and I are the noise, signal and interference power respectively. SINR denotes signal-to-noise-and-interference power ratio. The ways to calculate SINR are divided into two parts shown at Eq. 2:

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

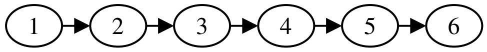

Figure 5: A string topology with 5 Hops.

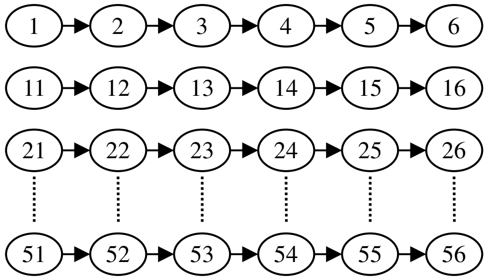

Figure 6: A 6 × 6 grid topology.

4.2. System model

The string and grid topologies shown in Fig. 8 and Fig. 9 are used for performance evaluation. In the both graphs, every node is 100 meters away from its direct neighbours. It is assumed that the W-CHAMB protocol is running on the IEEE 802.11a PHY at 5.2 GHz. The transmission rates vary from 6 Mbps up to 54 Mbps. The transmitting power of each node is 80 mW. The sensitivity levels of the receiver are shown in Table 1. The PHY mode for data packets is 16QAM1/2 and the corresponding PHY rate is 24 Mbps. With those settings, each node is only able to transmit with its direct neighbours and might cause interference to transmissions till 3 hops away.

Table 1: Key parameters for different PHY modes.

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

The traffic model is TCP Reno. It is assumed that every traffic generator produces a long-lived TCP traffic during its active period. Nodes 1, 11, 21, 31, 41 and 51 are TCP sources. In the string topology, nodes 2 to 6 might be a TCP Sink. In the grid topology, nodes 6, 16, 26, 36, 46 and 56 are TCP Sinks. Some important parameters are shown in Table 2 and Table 3. The results achieved in the string topology will be used as the baseline for analysing the traffic performance achieved in the grid case.

For convenience, Cwnd, VTT, MaxTCH and PDU are used to denote the TCP congestion window size (unit: TCP PDUs), VTT value (MAC frames), maximum TCH number for an ARQ connection and protocol data unit respectively.

4.3. String topology

In the part, the basic multi-hop performance of the W-CHAMB protocol is studied by the simpler string topology. Two baseline scenarios are evaluated. In the first case, every ARQ entity at any node is allowed to use all available TCHs, and TCP congestion window size of the source is accordingly set big enough in order to offer a high possible load. For the second case, every ARQ entity at a node is allowed to use up to 2 TCHs for transmission at one moment. Therefore, for a 5 hops transmission, all the traffic channels will not be run out of at any time. The highest achievable multi-hop throughput can be evaluated by the first scenario, while the second one is a reality case. Due to the QoS confinement, it is impossible to assign whole TCHs to one ARQ connection.

Table 2: Parameter setting in a MAC frame.

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

Table 3: Important settings in the PHY, MAC, RLC and TCP.

Other important settings in the PHY, MAC, RLC and TCP	
Transmission power	80 mW
PHY mode for Beacons	BPSK ½
PHY mode for data packets	16QAM ½
RLC PDU size	100 bytes
RLC Poll period	20 PDUs
Header of a MAC frame	8 bytes
Tx/Re Window size in SR-ARQ	100 PDUs
TCP Version	Reno
TCP PDU size	1500 bytes
TCP Sink PDU size	40 bytes

Fig. 7 and Fig. 8 show the throughput and delay performance respectively. From Fig. 7, it can be seen that the highest achievable throughput of 2, 3, 4, 5 hops reach 1/2, 1/3, 1/4 and 1/5 of the single hop throughput respectively. As shown in Fig. 4, the reuse distance of the string topology is 4 hops away. Therefore the whole bandwidth is shared by underline ARQ entities within the 4 hops, which leads to a channel utilization of 1/4. For the 5 hops transmission, the increased ARQ control overhead reduces the channel utilization from 1/4 to 1/5. The papers [8, 9] give the multi-hop TCP throughput of DCF networks in the exactly same scenario, where the throughputs of 2, 3, 4, 5 hops are 1/2, 1/3, 1/5 and 1/7 as the achievable throughput of single hop.

The throughput decline in the second case is due to the fact that the number of ARQ connections linearly increases with the number of hops, precisely, the hop number equal to ARQ connection number. Consequently the increased ARQ connections introduce more control overheads and result in longer Round Trip Time (RTT) values. There is no hidden

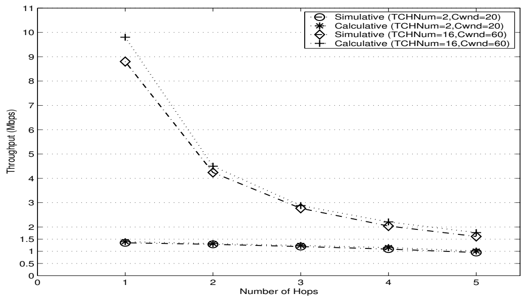

Figure 7: TCP throughput over the string network, VTT=120.

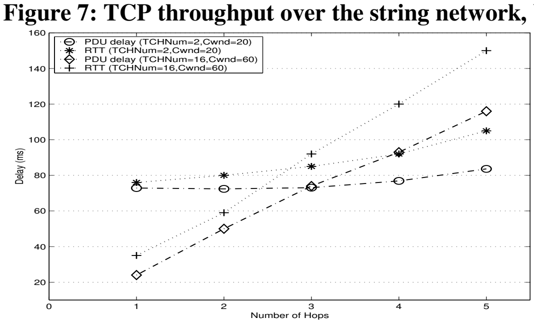

Figure 8: Delay performances over the string network, VTT=120.

station or exposed station problems in the network.

$$B(p) \approx \min\left(\frac{W_{\max}}{RTT}, \frac{1}{RTT\sqrt{\frac{2bp}{3}} + T_0 \min(1, 3\sqrt{\frac{3bp}{8}})\, p(1+32p^2)}\right) \quad (3)$$

In Fig. 7, the calculated results are also plotted in a line by applying the measured RTT values into Eq. 3 from [13]. The simulation and calculation results comply very well.

Impact of TCP Congestion Window Size

From now on, our attentions are on the 5 hops transmission only: all the results shown in the rest of this sub-section are for the TCP connection set up between node 1 and 6.

Fig. 9 and Fig. 10 reveal the impact of the TCP congestion window size on the TCP traffic performance. Paper [8] found that a multi-hop TCP connection in DCF networks achieve the best throughput performance when the TCP congestion window is 3, because this relatively small window size results in the smallest network-wide interference. However, this number is really too small for an efficient TCP transmission. On the contrary, in W-CHAMB networks, the increase of the congestion window size leads to a higher throughput as in wired networks. Fig. 9 also indicates that the maximum number of TCH for an ARQ connection should be bigger enough in order to fully develop the benefits brought by increasing the congestion window size. The increase of TCP window size also might cause longer queue delays, further results in longer PDU delays as shown in Fig. 10. However, the use of more TCHs for a connection is able to mitigate the side effect.

Impact of the Max TCH Number for an ARQ Connection

In the W-CHAMB system, a number of TCHs can be used together to satisfy a specific QoS requirement. The more TCHs are used a better traffic performance would be. It is shown in Fig. 11 and Fig. 12 that the use of more TCH helps

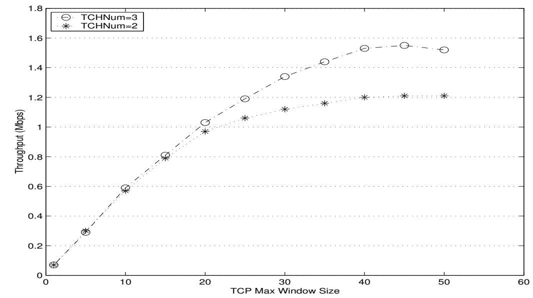

Figure 9: Impact of TCP Cwnd on the TCP throughput, VTT=120.

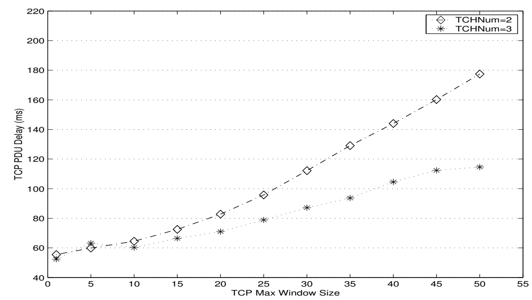

Figure 10: Impact of TCP Cwnd on the TCP PDU delay, VTT=120

to enhance both the throughput and delay performance. But if there is no data in a TCH over than a certain time, this reserved TCH will be released. This is why the extra TCHs do not help to improved performance any more when the offered load is not too big (Cwnd reflects the provided traffic load).

Impact of VTT Value

A longer VTT of a TCH leads to a higher throughput and a lower transmission delay as indicated in Fig. 13 and Fig. 14. However the throughput and delay stay stable regardless of the VTT value when the VTT values are over than 120 MAC frames. The 5 hops TCP connection cannot generate a continuous flow since a TCP source stop pulling down data packets utill receiving an acknowledgement. A TCH is released if no data passes by. The relative long RTT values of the TCP transmission cause the release of a TCH before the expiration of the VTT.

4.4. Grid topology

As shown in Fig.6, there are 36 nodes spreading over an area of 500m x 500m in the grid topology. Each TCP connection spans 5 hops. The transmission pairs have been described in the §4.2. Amount of TCP and ARQ connections are 6 and 30 respectively. Two scenarios are used here. The first one is called static case, where all the TCP connections are started and terminated simultaneously. The fairness, spatial reuse and impact of key parameters are investigated here. The further studies on the stability, fairness and spatial reuse performance will be conducted by using the dynamic case, where connections will be dynamically started or terminated.

Static Case

The increase of TCP congestion window size is a way to increase the offered load. Consequently, the more contentions and serious interference will appear. From Fig. 15, it can be found that the increase of load does not result in the performance degradation. On the contrary, the throughput of each TCP transmission increases with the load. The achievable

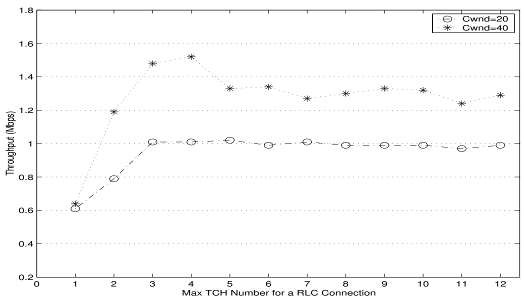

Figure 11: Impact of the maximum TCH number for an ARQ connection on TCP throughput, VTT=120.

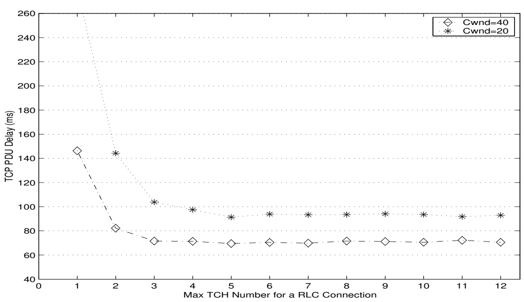

Figure 12: Impact of the maximum TCH number for an ARQ connection on TCP PDU delay, VTT=120.

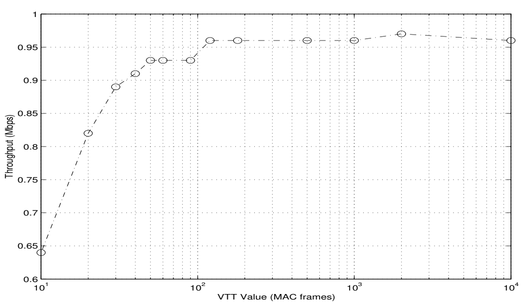

Figure 13: Impact of VTT on TCP throughput, Cwnd=20, MaxTCH=2.

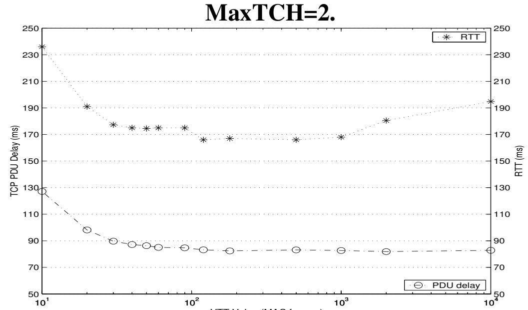

Figure 14: Impact of VTT on TCP PDU delay, Cwnd=20, MaxTCH=2.

aggregate throughput (1.3Mbps) in the grid topology is 20% less than the highest achievable throughput in the single 5-hop TCP transmission case (1.61Mbps) as indicated in Fig. 7, with the substantially increased ARQ connection number (from 5 to 30). This result implicates that the W-CHAMB protocol performs well in the serious interfered environment. The spatial reuse also helps the performance improvement. Special attention should be paid here that each transmission achieves almost same throughput under various loads, which means all the TCP connections fairly share the bandwidth.

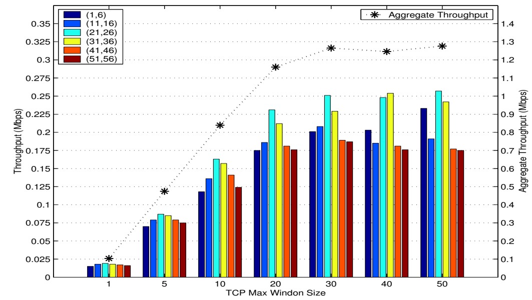

Figure 15: Impact of TCP congestion window size on throughput over the grid topology, VTT=120, MaxTCH=2.

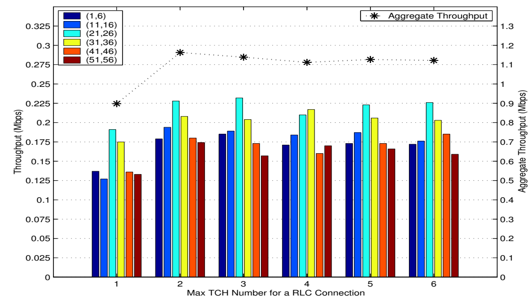

Figure 16: Impact of the maximum TCH number for an ARQ connection on throughput over the grid topology, VTT=120, Cwnd=20.

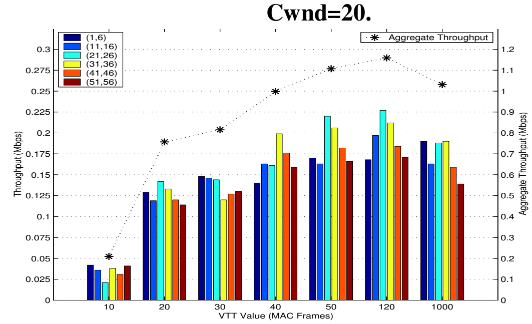

Figure 17: Impact of VTT on throughput over the grid topology, Cwnd=20, MaxTCH=2.

Under overload situations, putting into more TCHs for an ARQ connection does not yield an increase of throughput as indicated by Fig. 16. Although W-CHAMB networks have very good spatial reuse ability, the amount of bandwidth however has been fairly shared by ARQ connections. The increased waiting times caused by the increased contentions produce longer RTT values, which further result in the reduction of generating traffic. In this situation, one TCH or at most two TCHs is able to satisfy the transmission.

As shown in Fig.17, the throughput is improved with the VTT before the VTT reach 120 MAC frames. After that, throughputs stay the almost same regardless of the VTT.

Dynamic start and Release of Connections

In [7], the author pointed out the existence of the serious unfairness problem in DCF wireless multi-hop networks by running a simple scenario where two connections start at different moments. Now we design a more serious scenario also based on the grid topology to further test the performance of W-CHAMB multi-hop networks.

The TCP connections starting and stopping at given times are shown in Fig. 18. Sender/Receiver groups (1, 6) (21, 26) and (41, 46) start to transmit at 0 second. (11, 16), (31, 36) and

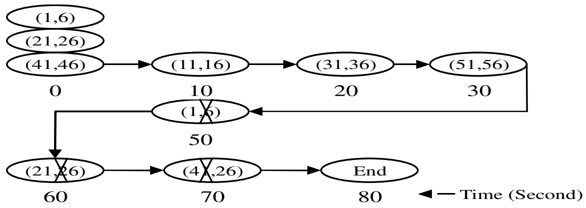

Figure 18: The change pattern of TCP connections during the run time.

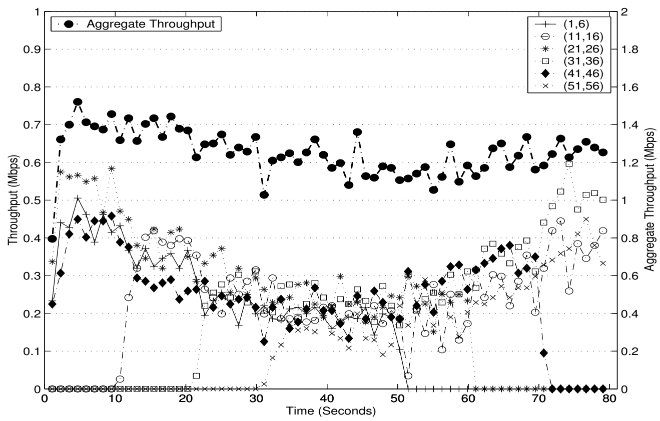

Figure 19: The throughput trace of each TCP connection and their aggregate value over the grid topology. The TCP connection changing pattern is specified in Fig.21, VTT=120, Cwnd=20, MaxTCH=2. Throughputs are measured every 1.2 s.

(51, 56) join the network and begin their transmissions one after the other at the time instants 10, 20, 30 second respectively. After sharing the bandwidth by 6 TCP connections for a duration of 20 seconds, the groups (1, 6), (21, 26) and (41, 46) stop their TCP connections at the time instants 50, 60 and 70 second, respectively. The groups (11, 16), (31, 36) and (51, 56) keep transmitting till the end of the simulation.

The simulation trace is plotted in Fig. 19. In the period of [0, 10] (second), the throughputs of each existing transmission are around 0.45 Mbps, and the aggregate throughput of three transmissions is 1.4 Mbps. With joining of another three transmissions one by one till the 30 second, the throughput of each transmission goes down a little till to 0.22 Mbps. The aggregate throughput goes down a little bit as well, since the amount number of ARQ connections goes up from 15 to 30. The increased control overhead results in this small reduction in the aggregate throughput. In comparison with this change, from the 50 second on, the gradual releases of transmissions from groups (1, 6), (21, 26) and (41, 46) cause both the throughput of remaining transmissions and aggregate throughput to return to their previous levels. All the transmissions go on very stably during all the running time. There is no sudden stop, increase and reduction of each running transmission in response to the joining and releasing actions. A more important result is that every running transmission achieves almost same throughput at every moment, which implies that the fairness is very good in the heavily interfered network.

5. Conclusions

This paper introduces the latest research progresses of the W-CHAMB protocol, with an emphasis on the features relating to multi-hop operation. In this article, we extend the prioritized access procedure from one stage to two stages. The new scheme significantly increases the probability that there is only one winner node in every contention and thereby minimizes the overall contention. Based on this change, we propose the FA algorithm, ensuring the fairly share of bandwidth among end-to-end connections in the multi-hop environment. We propose the On-demand-TDD scheme by using the Busy-E-Signal. With this scheme, the channel utilization of this TDMA-based system is enhanced quit a lot, especially when the traffic flow has asymmetric relation. We also propose the VTT concept, which idea is used to help prevent an excess use of a TCH by long lived streams.

The extensive simulations are performed by evaluating the TCP performance over multi-hop networks on the string and grid topologies. To our knowledge, the paper shows the best multi-hop performance of a system in term of achievable throughput, fairness and stability that is reported so far.

REFERENCES

[1] IEEE std. 802.11a: “Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer in the 5 GHZ Band,” 1999.

[2] IEEE Std. 802.11, “Wireless LAN Media Access Control (MAC) and Physical Layer (PHY) Specification,” 1999.

[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] S. Xu and T. Saadawi, “Does the IEEE 802.11 MAC Protocol Work Well in Multi-hop Wireless Ad Hoc Networks?” IEEE Communications Magazine, pp. 130-137, Jun. 2001.

[8] Z. Fu, P. Zerfos and H. Luo, “The Impact of Multi-hop Wireless Channel on TCP Throughput and Loss,” in Proc. IEEE INFOCOM 2003, San Francisco, USA, Apr. 2003.

[9] R. Draves, J. Padhye and B. Zill, “Comparison of Routing Metrics for Static Mult-hop Wireless Networks,” In Proc. SIGCOMM 04, Portland, Oregon, USA , Aug.30, 2004.

[10] 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.

[11] M. Lott and I.Forkel, “A Multi-wall-and-floor Model for Indoor Radio Propagation,” in Proc. IEEE VTC Spring 2001, Greece, May 2001.

[12] J. Khun-Jush, et al., “Structure and Performance of the HIPERLAN/2 Physical Layer,” IEEE VTC Fall 1999, Amsterdam, Sep. 1999.

[13] J. Padhye, V. Firoiu, D. Towsley and J. Kurose, “Modeling TCP Throughput: A Simple Model and its Empirical Validation,” ACM SIGCOMM, Vol. 28, No. 4, Oct. 1998.