10th Aachen Symposium on Signal Theory,
20-21 Sept. 2010. ISBN 3-8007-2610-6

Multihop Traffic Performance of IEEE 802.11a, HiperLAN/2 and W-CHAMB*

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Abstract

This paper presents a new self-organising wireless broadband multihop network (W-CHAMB: Wireless CHannel-oriented Ad-hoc Multihop Broadband network). A channel-oriented MAC protocol that is based on dynamic packet reservation is proposed for W-CHAMB. Energy signals (E-signals) are used to realise distributed access priorities of wireless stations, to solve the hidden station problem and to achieve a MAC level acknowledgment (ACK) for a fast ARQ. The multihop traffic performance of IEEE 802.11a, ETSI HiperLAN/2 and W-CHAMB is intensively evaluated stochastically based on a prototypic implementation of the protocols under various traffic loads. Results are presented and compared for networks with different scenarios.

1 Introduction

A self-organising broadband multihop network will be best suited to be operated in the 5-6 GHz license-exempt spectrum because there is a high capacity of 455 MHz in Europe. The respective frequencies have very limited ability to penetrate obstructions and have very unpredictable propagation characteristics so that frequency planing is impossible there. Although the most common way to realize a broadband network is to use a centrally controlled MAC protocol to realise statistical multiplexing of bursty multimedia traffic sources and to guarantee QoS (see, e.g., HiperLAN/2 [2]), self-organisation of a network appears to be not feasible, or even impossible, to implement based on a central controller. Multihop transmission must be considered as a means to achieve a reasonable communication coverage due to the limited transmission range of broadband signals at 5 GHz.

The most challenging task to realize such a self-organizing broadband multihop network with QoS guarantee is to design an efficient MAC protocol. The design challenges are to provision different QoS requirements to different service classes and to realise the statistical multiplexing of bursty traffic in a self-organising multihop networking environment.

* This work has been supported by the German Federal Ministry of Education, Science, Research and Technology under the Multihop project

This paper examines the suitability of MAC protocols of ETSI HiperLAN/2 (H/2) and the DCF/PCF of IEEE 802.11 for a self-organizing broadband multihop network. Then, we propose our W-CHAMB MAC protocol. These three MAC protocols represent three completely different approaches to share a common wireless channel among WSs. The traffic performance of these three MAC protocols is compared based on stochastic computer simulation.

2 ETSI HiperLAN/2 - a centralised solution

H/2 is a scheduler oriented high performance radio technology specified by the European Telecommunication Standards Institute (ETSI) [3][4][5]. The system operates in the 5 GHz license-exempt frequency band. H/2 provides a uniform broadband wireless access platform to carry any type of user data, such as Ethernet frames, ATM cells and IP packets.

2.1 H/2 MAC protocol

In H/2, a fully centralized MAC protocol based on Dynamic Slot Assignment (DSA++ [2]) is specified. A central controller assigns radio resources within a H/2 MAC frame. The assignment of resources may change from frame to frame. The fixed length of a H/2 MAC

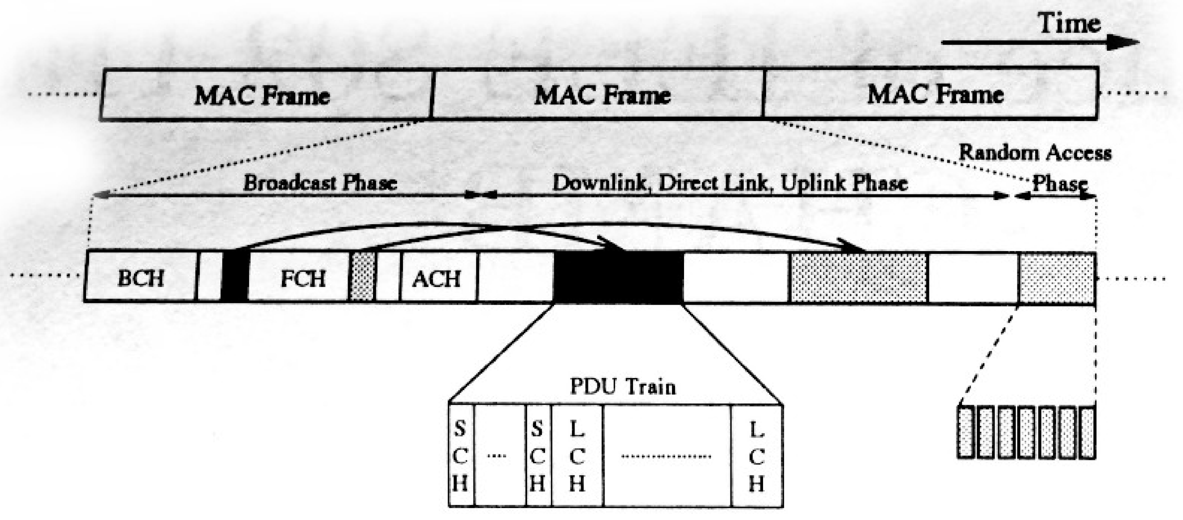

Figure 1: H/2 MAC frame

frame ($t_{frame} = 2ms$) consists of three major phases as shown in Fig. 1. The broadcast phase is used to transport the control information and carries the Broadcast Control Channel (BCCH), the Frame Control CHannel (FCCH) and the Random Access Feedback Channel (RFCH). The BCCH transmits control information through the Broadcast CHannel (BCH) protocol data unit (PDU) in each MAC frame. It provides information about transmission power levels, starting point and length of the Frame CHannel (FCH) and the Random CHannel (RCH). The BCCH is 15 bytes long and is transmitted using the most robust modulation scheme available, i.e. BPSK 1/2 [3]. The RFCH provides information through the access feedback CHannel (ACK) on access attempts made by WSs in the RCH of the previous MAC frame. The downlink, direct link and uplink phase are used to transport data PDUs between the central controller and WSs or between WSs directly. The random access phase is used for the initial access to the network, for handover indication and for requesting radio resources.

Two kinds of PDUs, the long PDU (LCH PDU) and the short PDU (SCH PDU) are specified. A LCH PDU is 54 bytes long and contains 48 byte payload, which is the same as that of an ATM cell. An SCH PDU is 9 bytes long and contains 52 bits for signaling data. In order to reduce physical overhead, all LCH and SCH PDUs in one MAC frame belonging to connections of the same MT are combined to a PDU train. A detailed description of the H/2 MAC protocol can be found in [4].

2.2 H/2 HEE

The communication between home devices including the support of IEEE 1394 is another purpose of H/2. The H/2 Home Environment Extension (HEE) specifies an ad hoc network configuration to allow plug-and-play operation. The H/2 HEE uses the same MAC protocol as described in 2.1. The central control function is performed by a Central Controller (CC). The network is self-organised by two functions: CC selection and CC handover [5].

The H/2 HEE is designed for one single cluster. A multihop networking concept is presented in [11] to extend HEE to a multi-cluster and multihop network. Terminals of two different clusters may communicate via terminals that are able to participate in both networks. A terminal can participate in two cluster at the same time, if it is in the transmission range of both CCs in the respective clusters. In [13] a Multiple-Frequency Forwarder concept is presented to realise such a terminal.

To extend the HEE to a multihop network can be viewed as a centralised solution for a self-organising broadband multihop network. CC Selection and CC handover may be suited for a home environment, but appear to be too complicated for a broadband wireless Internet access network. Moreover, Multiple-Frequency Forwarder and multi-cluster operation suffers from the inherent spectrum inefficiency.

2.3 H/2 with FMT

To enhance the communication range of H/2, a Forwarding Mobile Terminal (FMT) concept is presented in [10]. A Remote Mobile Terminal (RMT) is an MT that cannot communicate directly with the AP on the one hop link but needs a forward link for two hop communication. An MT associated with the AP and located at the edge of the AP coverage area may perform the function of a forwarder. In [10] a possible implementation of the time shared forwarding concept without large modification to the existing H/2 specification is proposed. A H/2 MAC sub frame is generated by the FMT to communicated with the RMTs associated with it. The uplink phase capacity assigned to the FMT in the H/2 MAC Frame, see Fig. 1, is exploited by the FMT to define the sub frame and to transmit its own uplink traffic if any. The structure of the sub frame is identical to that of the MAC frame.

3 DCF/PCF of IEEE 802.11 - a packet-oriented solution

In contrast to H/2, IEEE 802.11 uses a distributed access scheme that consists of DCF and PCF [8]. DCF is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and shall be implemented in all stations. DCF can work without any AP and can realise multihop communication. PCF is an optional access method that is implemented on top of the DCF. PCF is a mechanism used in IEEE 802.11 WLAN to achieve a contention free access to support time-bounded service by a point coordination station.

3.1 DCF

As an example, Fig. 2 shows the basic operation of the DCF access mechanism. Each time the medium becomes idle, the station waits for a DIFS (Distributed Inter Frame Space) and then stepwise decreases the

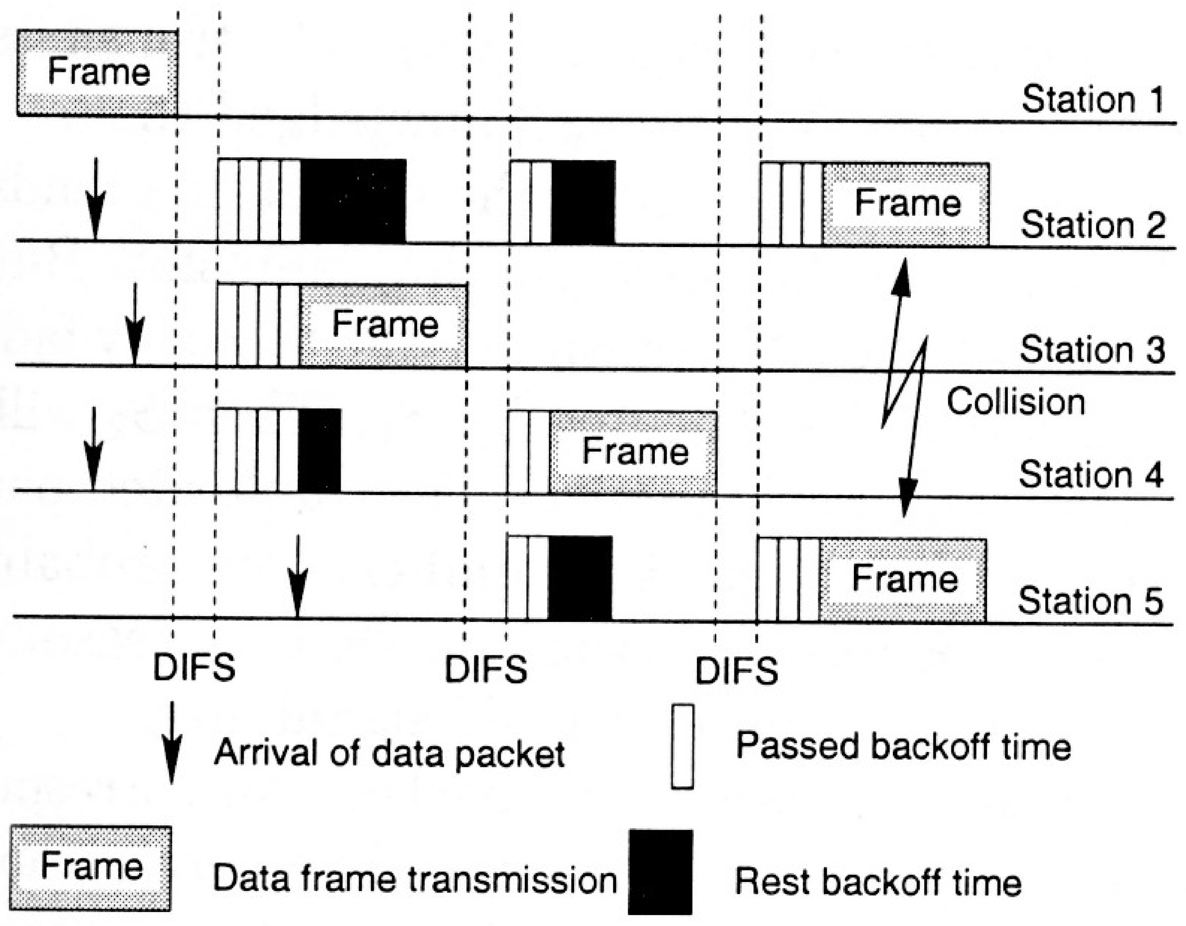

Figure 2: IEEE 802.11 basic access mode

back-off timer. As soon as the back-off timer expires, the station transmits its packet at once. The transmitted packet is acknowledged by the receiver after a SIFS (Short Inter Frame Space) if the packet is received correctly.

To deal with hidden stations and to reduce the duration of a collision cycle, an RTS/CTS (Request To Send/Clear To Send) mechanism is specified in IEEE 802.11. If the size of a packet to be sent is larger than an RTC/CTS threshold, RTS and CTS short packets are exchanged before the data packet is transmitted. RTS and CTS contain a duration field that specifies the time necessary to complete the transmission cycle. This information is used to update the Net Allocation Vector (NAV), a timer used to defer a station from accessing the medium.

3.2 PCF

As DCF has no means to support time-bounded service, IEEE 802.11 defines PCF to permit a Point Coordinator (PC) to have priority access to the medium. Stations which are able to respond to polls by the PC are called Contention Free Pollable (CF-Pollable). Besides the AP, only CF-Pollables are able to transmit frames according to the PCF. So PCF has no multihop ability.

4 W-CHAMB - a channel-oriented solution

Inspired from GPRS (General Packet Radio Service) and ETSI/DECT concepts, we developed a channel-oriented solution - W-CHAMB (Wireless CHannel-oriented Ad-hoc Multihop Broadband) network - for a self-organizing broadband wireless network. W-CHAMB adopts the key idea of GPRS, that is statistical multiplexing of bursty traffic through packet reservation, and the most advanced feature of DECT, that is dynamic channel selection according to the measured signal level RSSI (Radio Signal Strength Indicator) [16]. It differs from the GPRS and DECT with its ability to operate in a multihop environment and in a fully distributed manner. The most significant feature of W-CHAMB is that it meets QoS parameters for different classes of service and realizes statistical multiplexing of bursty traffic in a fully distributed and efficient manner.

4.1 W-CHAMB Channel structure

Transmission of packets in W-CHAMB networks is channel-oriented. The transmission time scale in W-CHAMB networks is organized in periodic frames, each containing a fixed number of time slots, see Fig. 3. All WSs of the network are synchronized on a frame and slot basis.

To use channel resources more flexibly for heterogeneous applications, periodic slots are used as physical channels to provide transmit capacity for several logical channels (LCH), e.g. LCH1/2 uses one slot every two frames, see Fig. 3. One or more slots of a MAC frame are used as access channel (ACH), where a number of energy signals and an access signaling packet (*acc s-pkt*) can be transmitted. The other slots are used as physical traffic channels (TCHs), each for transmission of one data packet per frame. Each data packet has a user part, such as an ATM cell, and a packet header containing information, such as packet identifier, sequence number, time information, etc., see [9].

At the end of a MAC frame a number of minislots that carry energy signals (E-signals) follow. Each minislot is associated with a TCH. Each E-signal is only a single on-off pulse of the unmodulated carrier, so that the related overhead is generally quite small. E-Signals could alternately be sent in parallel on a narrow band frequency channel to keep the overhead caused by E-Signals negligible. Two E-signals may be sent on one minislot. One is the Busy-E-signal to solve the hidden station problem. The receiving WS sends a Busy-E-signal to indicate to its neighbor WSs the corresponding TCH is its current reserve channel. The other one is the ACK-E-signal that is used to acknowledge a correctly received packet. A duplex channel would require two TCHs with related minislots that can be realized either by TDD (Time Division Duplex) operation of a TCH or by independent TCHs.

4.2 Dynamic Channel Reservation

As an example, we demonstrate the procedure of dynamic channel reservation (DCR) for S_1 to send an information burst to S_2, see Fig. 3. At the beginning of the channel reservation, S_1 contends for transmitting an *acc s-pkt* via the ACH using the distributed access priority. The *acc s-pkt* contains a set of free LCHs that have a low noise level and could be used in

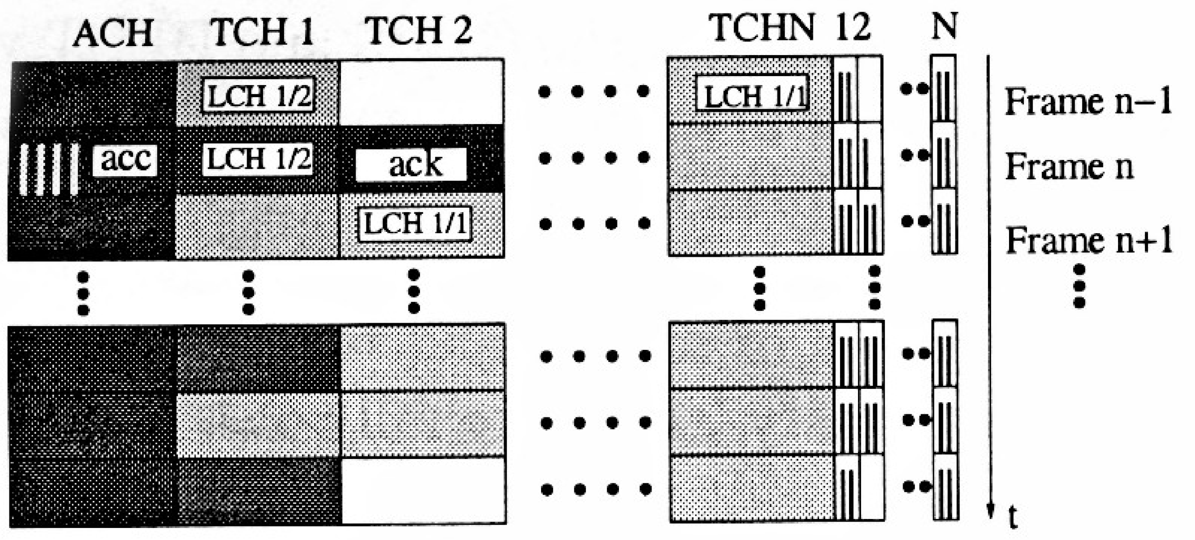

Figure 3: W-CHAMB channel structure

the view of S_1. In the event that S_1 did send the *acc s-pkt*, and the addressed station, e.g. S_2, could successfully receive this *acc s-pkt* and could find at least one of the LCHs proposed by S_1, to be also free in the view of S_2, it responds to S_1 with an acknowledgment (*ack*) *s-pkt* via the selected LCH, e.g. LCH1/1 on TCH 2 in Fig. 3, and starts sending an Busy-E-signal on the corresponding minislot 2. By this procedure, a LCH is reserved between S_1 and S_2. All other WSs in the detection range of S_1 and/or S_2 will mark this LCH as reserved. The hidden station problem is resolved by the Busy-E-signal sent by S_2. At the end of its information burst, S_1 stops transmitting on the reserved LCH and S_2 stops sending the Busy-E-signal on the corresponding minislot. WSs in the range of S_1 and/or S_2 that detect then the TCH 2 unused will mark it in their local channel occupancy list free again.

4.3 MAC level ACK

The receipt of a packet on the reserved TCH requires the receiving WS to respond with an acknowledgment. This technique is known as positive acknowledgment. The receiving WS in W-CHAMB network sends an ACK-E-signal on the corresponding minislot for the purpose of a positive acknowledgment if a packet is received on the reserved TCH.

Lack of receipt of an expected corresponding ACK-E-signal on the minislot indicates to the sender that an error on the reserved TCH has occurred. The errored PDU shall be repeated on the next transmission opportunity.

An ACK-E-signal on the minislot is uniquely associated with a reserved TCH by setting the decision signal level, called ACK signal level, for the ACK-E-signal appropriately. The ACK signal level should be much larger than the detection level, but smaller than or same as the decode level of the receivers of WSs. Its power might even be controlled according to the actual needs. To describe the operation of MAC level ACK by ACK-E-signals, we assume that S_1 has sent a packet to S_2 on the reserved TCH n. There are three possible results of this packet:

(1) S_2 successfully receives the packet and sends an ACK-E-signal on the corresponding minislot. S_1 detects this ACK-E-signal with a sufficiently high signal level (larger than ACK signal level). The transmission of this packet on TCH n is acknowledged then.

(2) S_2 successfully receives the packet and sends an ACK-E-signal on the corresponding minislot. But S_1 can not detect the ACK-E-signal due to heavy fading. The packet shall be repeated by S_1. Then S_2 will receive the correct packet twice. The duplicated packet is filtered out by the packet number. The probability that a packet is received twice can be kept reasonably low by selecting a suitable ACK signal level.

(3) S_2 does not receive the packet. No corresponding ACK-E-signal is sent by S_2. The correct operation of the MAC level acknowledgment requires that S_1 shall not receive any ACK-E-signal for TCH n sent by another WS that would cause a false acknowledgment. As no WS in the detection range of S_1 may reserve TCH n for receive, no ACK-E-signal for TCH n shall be sent by other WSs except S_2 in the detection range of S_1. WSs which are out of the detection range of S_1 may send ACK-E-signals for TCH n due to the spatial reuse of TCH n. But those ACK-E-signals will reach S_1 with a much lower signal level than the agreed ACK signal level. So no false acknowledgment shall be received by S_1. The errored packet sent on TCH n will be retransmitted until it is correctly received.

5 Performance evaluation

Intensive stochastic computer simulations have been used to evaluate and compare the traffic performance in H/2, IEEE 802.11a and W-CHAMB systems. The physical layer of W-CHAMB uses the same OFDM modulation schemes as standardized for IEEE 802.11a [6] and H/2 [3]. The size of a data packet sent in one slot in W-CHAMB is 9 OFDM symbols (36 us). Each packet contains a 6 bytes packet header that is not counted in the throughput performance. The slot duration is 45 us including 9 us for physical overhead. The number of slots of one W-CHAMB MAC frame is 16.

5.1 One hop scenario

Fig.4 shows a one hop scenario for a fully connected wireless LAN. It consists of an AP serving a video stream download (MPEG) and a duplex voice connection (N-ISDN), and eight terminals exchanging Ethernet packets with their direct neighbor MTs in a circular way. The data rate of the Video traffic has been set to 5 Mb/s whereas the mean data rate of the LAN traffic has been varied to model different loads. Traffic loads of MPEG and Ethernet are read from trace files [19][20].

In the simulation, the transmission rate of H/2 is set to 27 Mb/s. The transmission rate of IEEE 802.11a is 24 Mb/s. The PCF of IEEE 802.11 with Contention

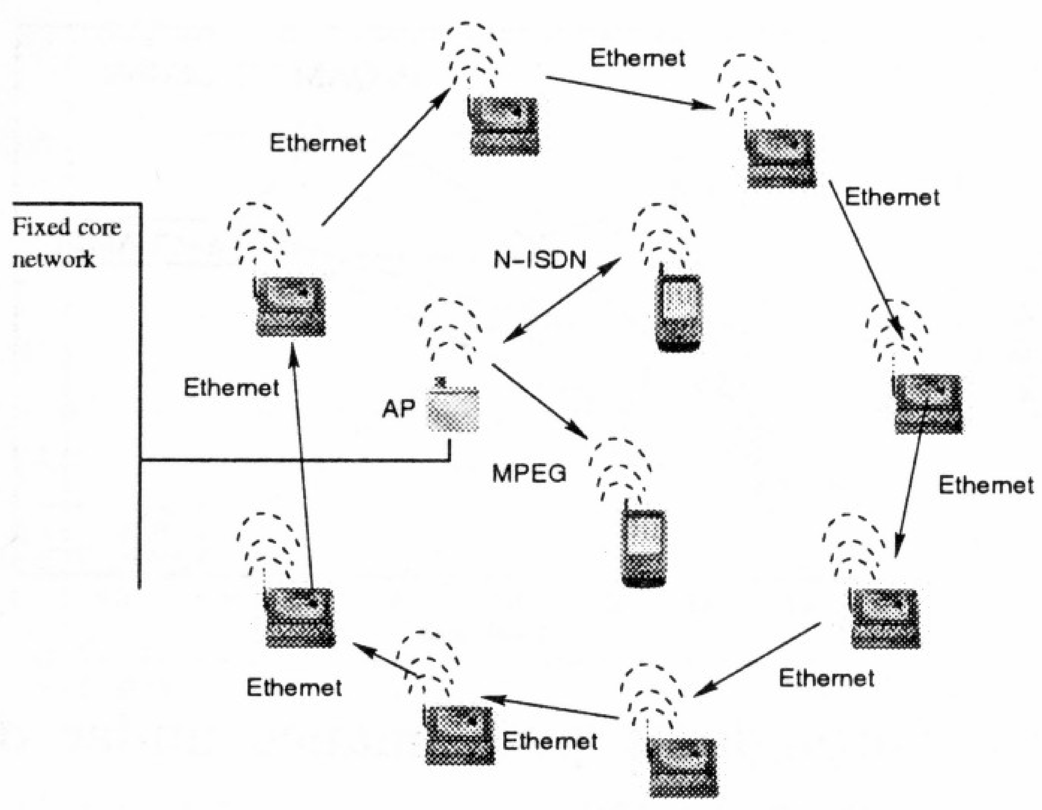

Figure 4: One hop scenario

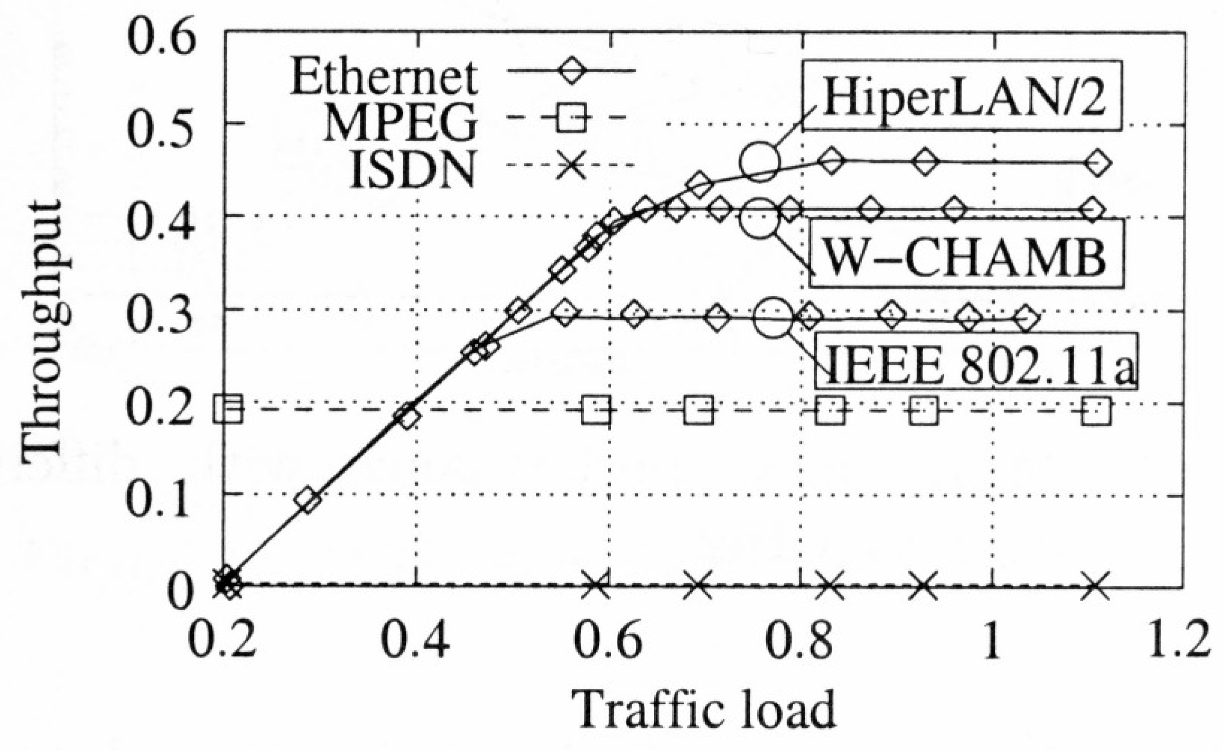

Figure 5: One hop throughput performance

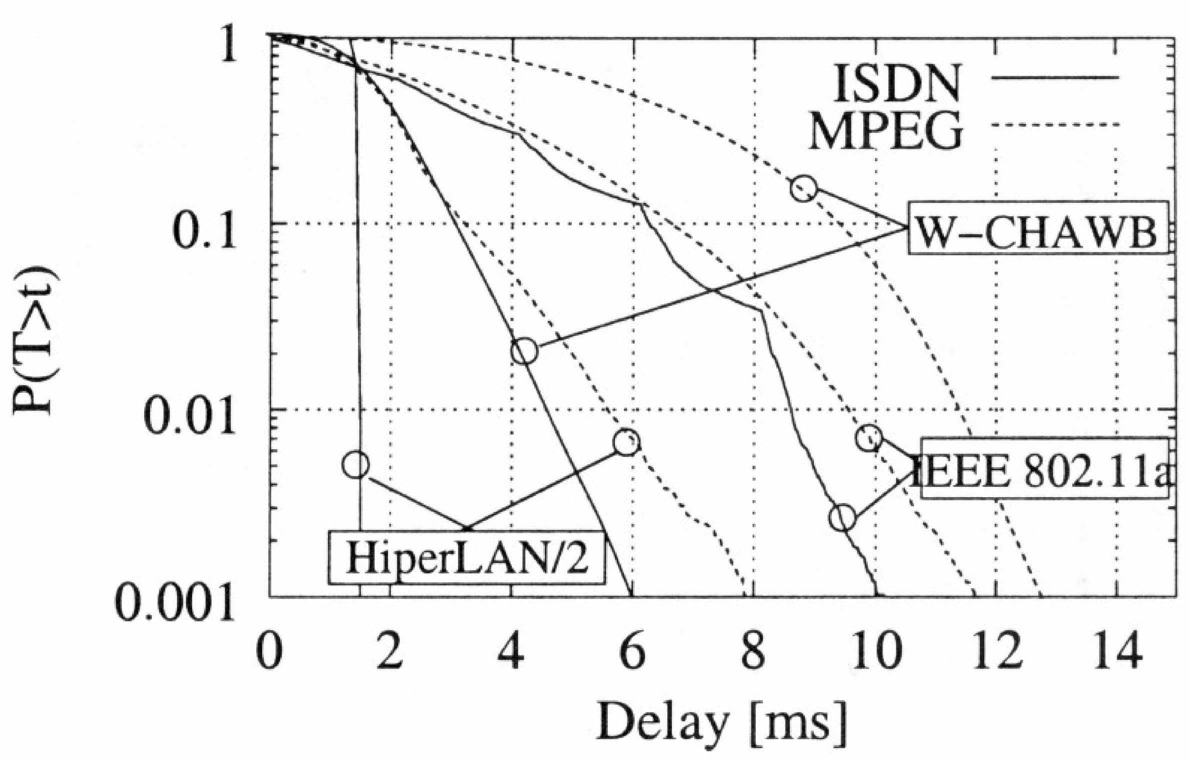

Figure 6: CDF of MPEG and N-ISDN at high traffic load conditions

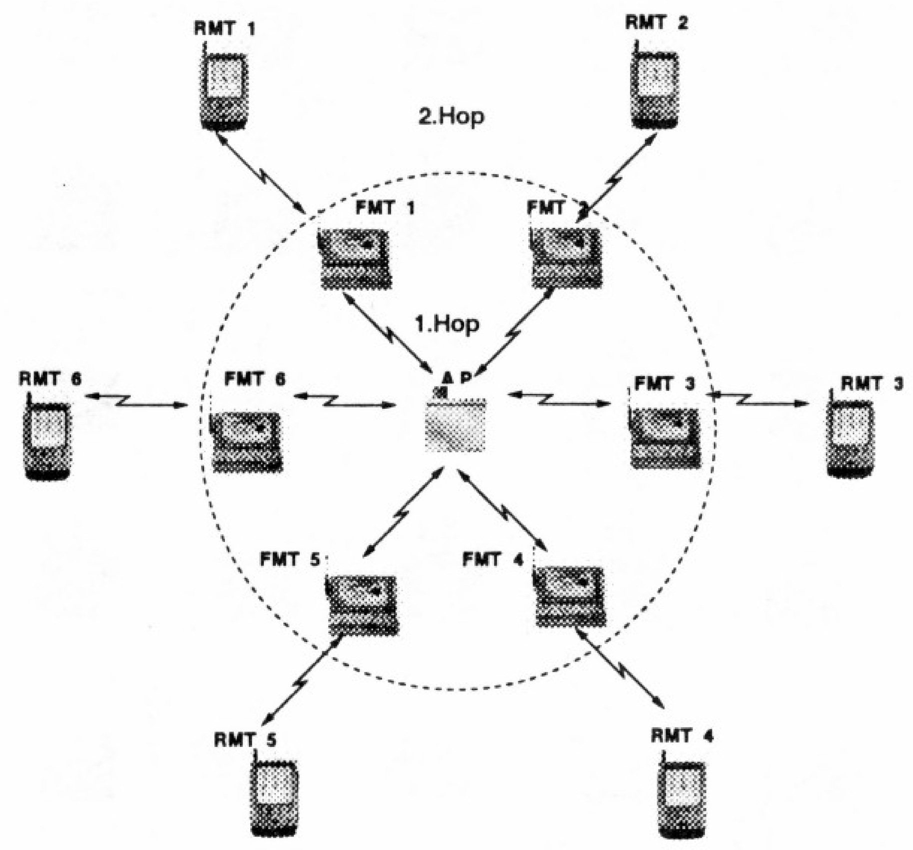

Figure 7: Two hop scenario

Free Repetition Interval of 10 ms is used to serve the N-ISDN and MPEG services that have priority over the Ethernet service. The transmission rate of W-CHAMB is also 24 Mb/s. Fig.5 shows the relative throughput of the different traffic flows under no bit errors where the load of the Ethernet service has been varied. In all systems the prioritized services N-ISDN and MPEG are served well under all load conditions, whereas the throughput for Ethernet is different. H/2 has the highest throughput for the Ethernet service. The throughput of W-CHAMB for Ethernet service is a little lower than that of H/2, but significantly higher than that of IEEE 802.11a.

The complementary distribution function (CDF) of the packet delay at high load conditions is shown in Fig. 6. Although W-CHAMB has neither a central controller like H/2 nor a point coordinator like IEEE 802.11, the packet delay of N-ISDN is bounded to 6 ms and the delay of MPEG is limited to 13 ms at the total traffic load of 0.75, which meets the requirements of high performance video. In this one hop scenario, H/2 has the the best traffic performance for all services.

5.2 Two hop scenario

Fig. 7 shows a two hop scenario with a central access point to a fixed network. Some MTs are placed out of the coverage range of the AP to to act as RMTs. The end-to-end user connections (i.e. connections between AP and RMT) are loaded with Poisson traffic. We use this scenarios to compare maximum throughput performance of IEEE 802.11a, H/2 with FMT and W-CHAMB.

In Fig.8 the maximum system end-to-end throughput of the three systems under transmission rates of 18 Mb/s, 36 Mb/s and 54 Mb/s is shown. The packet size with W-CHAMB is 9 OFDM symbols, equivalent to 81 bytes, 162 bytes and 243 bytes under transmission rates of 18 Mb/s, 36 Mb/s and 54 Mb/s, respectively. The respective packet sizes with IEEE 802.11a are 115 bytes, 196 bytes and 277 bytes, each including a 34 byte packet header. The packet size with H/2 is standardized as 54 bytes including 6 byte packet header under all transmission rates. From Fig. 8 we see that the throughput of IEEE 802.11a is very low due to short packet size and two hop transmission. For H/2 with FMT, an increasing number of FMTs that all are serving one RMT strongly decrease the capacity available for AP-to-RMT connections as more and more capacity is needed for the overhead introduced by the sub frames of the FMTs. In contrast to H/2 with FMT, an increasing number of FMTs increases the maximum throughput slightly because of the frequency spatial reuse of the decentralized MAC protocol of W-CHAMB.

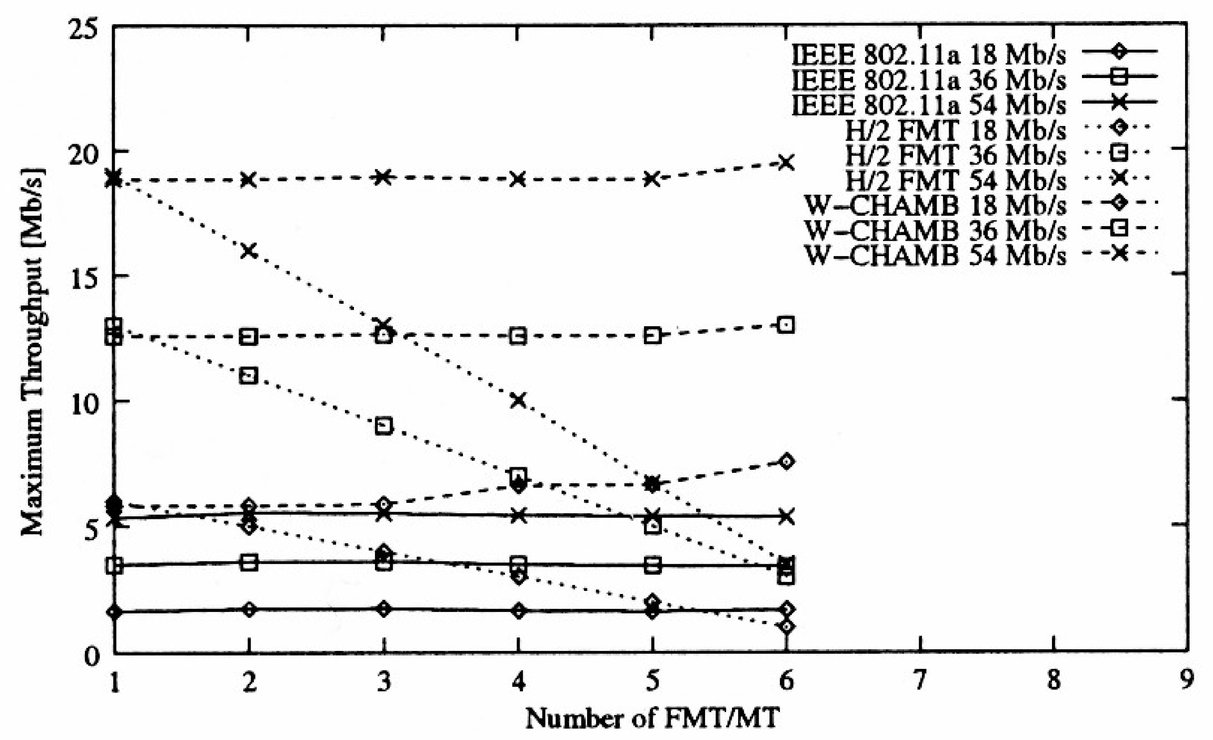

Figure 8: Maximum throughput performance

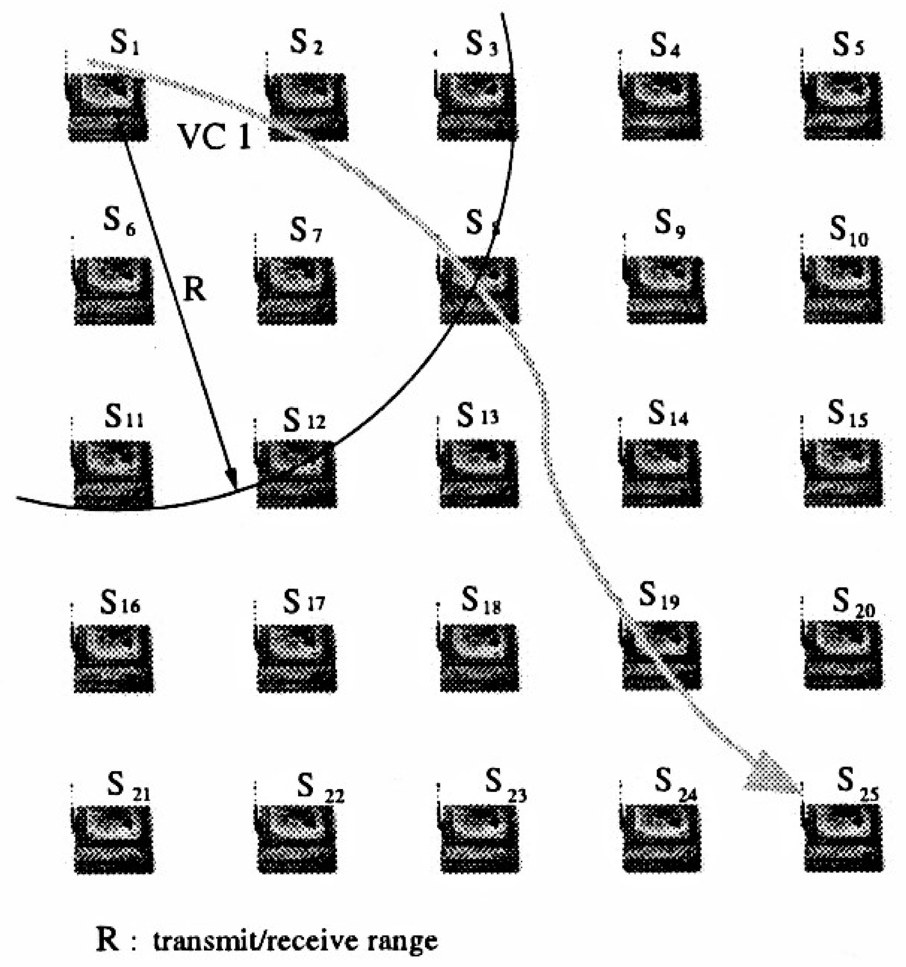

Figure 9: Multihop scenario

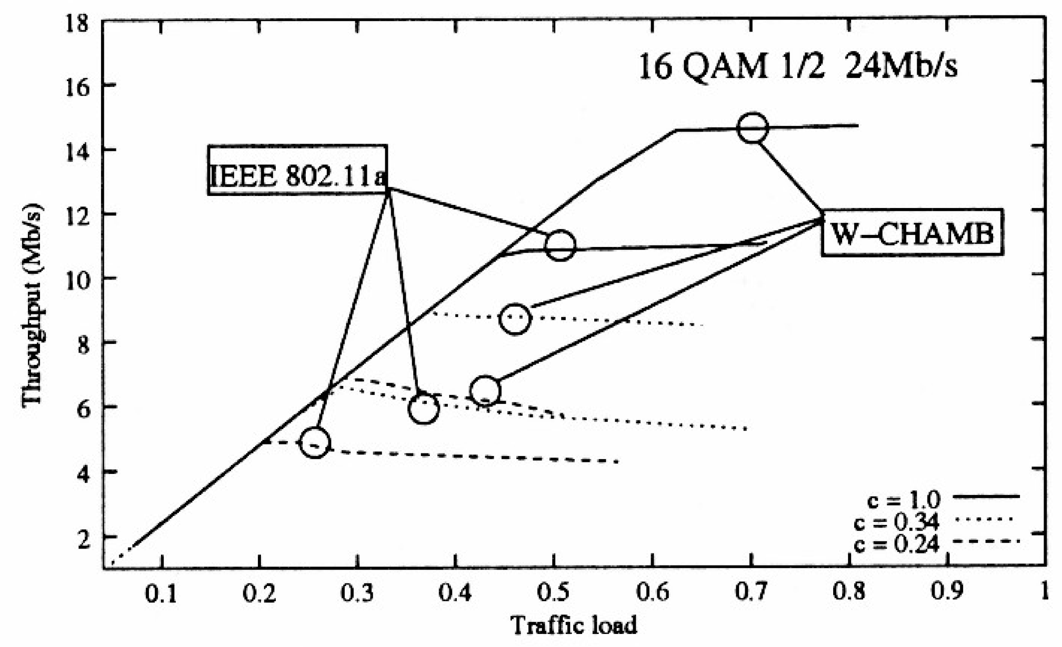

Figure 10: Throughput performance under different connectivities

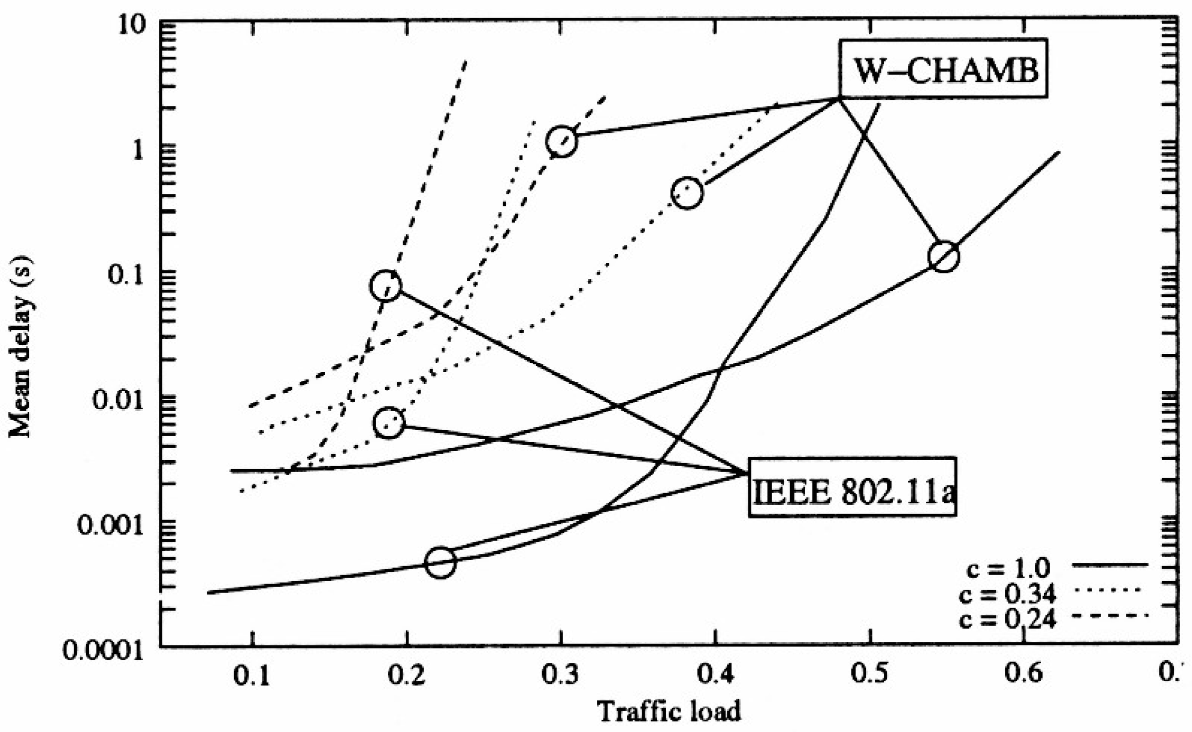

Figure 11: Mean delay performance with different connectivities

5.3 Multihop scenario

To study the traffic performance in a multihop scenario, a 5x5 square grid network with 25 WSs is used, see Fig. 9. A desired network connectivity is achieved by adjusting the fixed transmit power of the wireless stations accordingly. The connectivity is defined as the mean number of neighbors to a WS, normalized by the number of the maximum possible number of neighbors. $c = \frac{1}{N(N-1)} \sum_{i=1}^{N} n_i$, where n_i is the number of neighbors to station i, N is the number of stations in the network. This means that a fully connected network has a connectivity of 1. Each wireless station randomly selects another station as its traffic sink. The Min-hop routing algorithm is used to establish a multihop connection. Different from scenario of Fig. 7, no access to a fixed network is considered here, resulting in an unbalanced traffic distribution to WSs.

The packet error rate depends on the carrier-to-interference ratio (C/I) and packet size. The results of [17] concerning the relation between the C/I and the packet error rate are used as a reference. We assume that the power at the distance γ from the transmitter is $W = k\gamma^{-\alpha}$, where k is a constant for all stations. A typical value for WLAN environments is $\alpha = 4$.

To compare the traffic performance of W-CHAMB and IEEE 802.11a in the multihop environment, realistic packet sizes read from an Ethernet trace file [20] are used for the traffic load. The transmission rate is 24 Mb/s. Fig. 10 shows the throughput of W-CHAMB and IEEE 802.11a under different network connectivities. For both systems, the smaller the network connectivity is, the lower is the throughput. This is because at a smaller network connectivity more hops are necessary for an end-to-end connection. It can also be seen in Fig. 10 that the maximum throughput of W-CHAMB is much higher than that of IEEE 802.11a over all network connectivities. It appears that our channel-oriented MAC protocol is much more efficient than the packet-oriented one.

Fig. 11 shows the mean delay of W-CHAMB and IEEE 802.11a. The impact of the network connectivity on the mean delay in W-CHAMB and IEEE 802.11a can be clearly seen. With a larger network connectivity, a better delay performance can be achieved. It is interesting to see that IEEE 802.11a has a better overall mean delay performance than W-CHAMB as long as it is not saturated. The reason for that is that IEEE 802.11a can transmit a packet as large as 4095 bytes, whereas W-CHAMB has to segment large packets into 102 byte fragments at the transmission rate of 24 Mb/s. The fragments are transmitted over a number of W-CHAMB MAC frames as a packet train. However, IEEE 802.11a is not able to differentiate between service classes and the mean delay of all service classes together is a too rough measure to characterize a system.

The unique feature of W-CHAMB is QoS guarantee for real time traffic in a multihop network without any central control. This feature makes it best suited to be

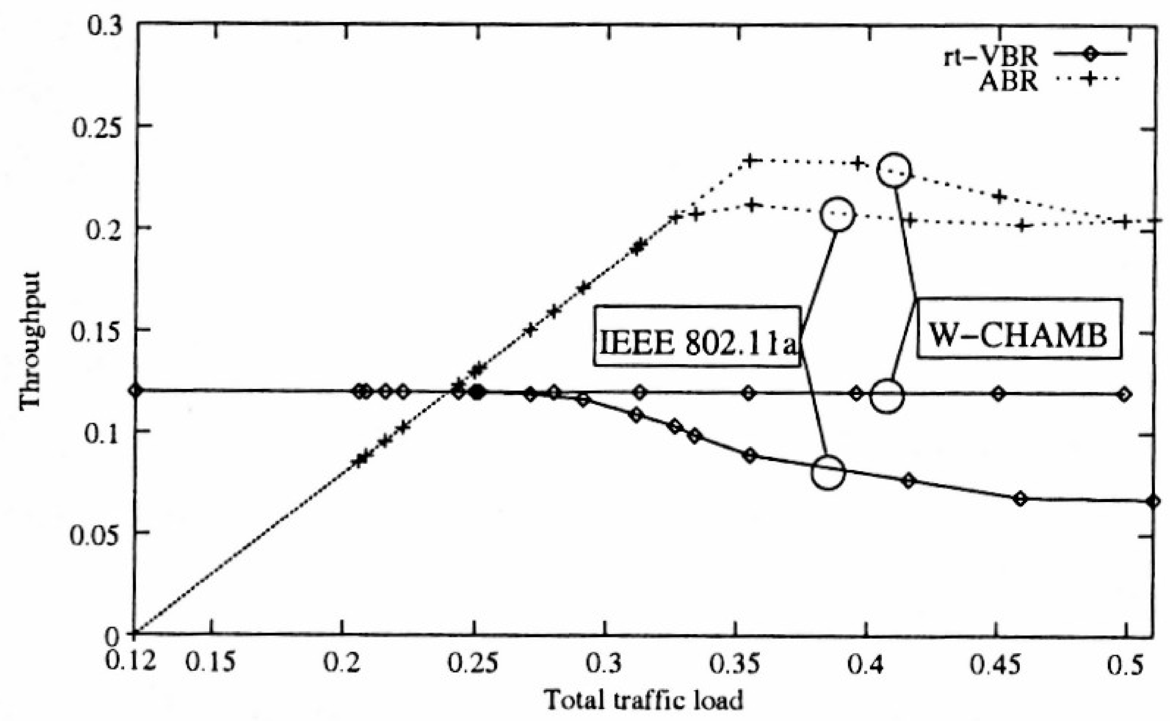

Figure 12: Throughput performance at c = 0.34

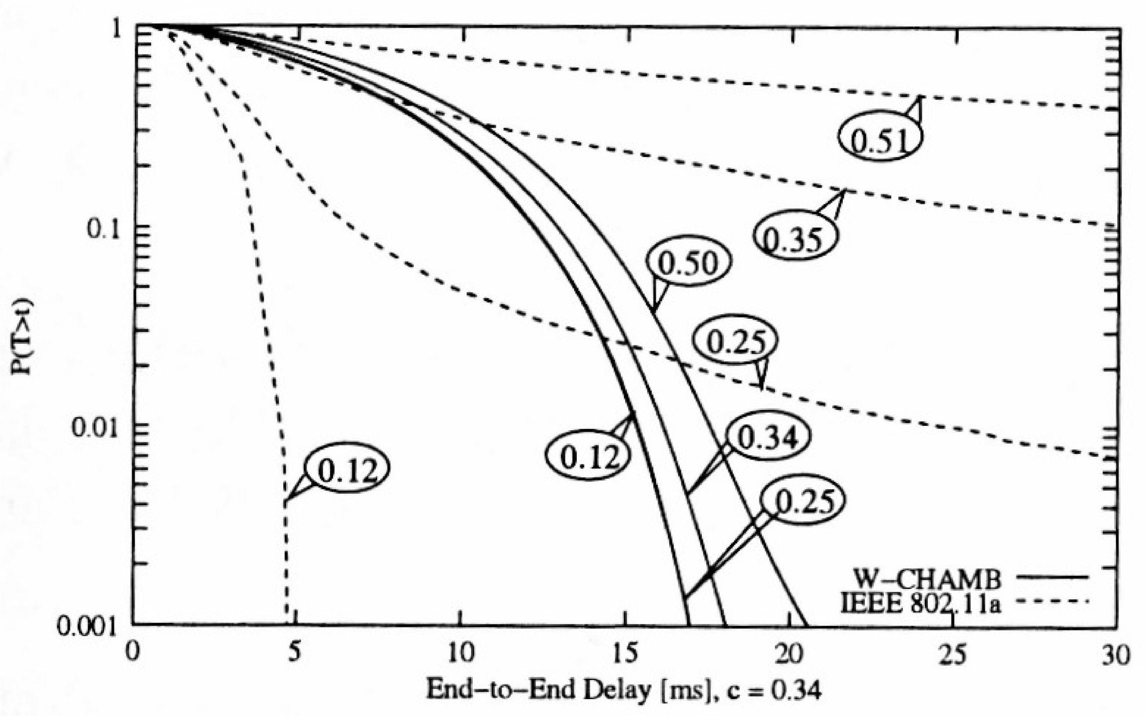

Figure 13: CDF of rt-VBR traffic at c = 0.34

applied as a self-organising wireless broadband multihop network. To evaluate the grade of the QoS support of real time traffic, we study the network shown in Fig. 9 at a connectivity of 0.34. Five stations are loaded with real time (rt)-VBR traffic. All other WSs have one ABR connection each. The packet size of rt-VBR traffic is modeled by an autoregressive Markovian process, with a mean of 3060 bytes and a maximum of 6120 bytes, yielding a burstiness factor of 2. The rt-VBR traffic source produces 24 packets per second. The packet size of ABR traffic is read from an Ethernet trace file [20]. The interarrival time of Ethernet packet read from the trace file has been varied to model different loads.

Fig.12 shows that the prioritized rt-VBR service is served with the same throughput under all load conditions in W-CHAMB, whereas the throughput of rt-VBR traffic decreases with the increasing traffic loads in IEEE 802.11a since a rt-VBR packet is dropped if its delay exceeds 30 ms. The maximum throughput of the ABR service is 0.25 and 0.21 in W-CHAMB and IEEE 802.11a, respectively. The difference in maximum throughput for ABR services of W-CHAMB and IEEE 802.11a is less significant than that indicated in Fig 10 under a pure Ethernet traffic load. There are three reasons to explain this result. One is that ABR transmissions are frequently interrupted and resumed later in W-CHAMB to free a channel for rt-VBR traffic at a high traffic load. The second is that most packets of rt-VBR traffic are much larger than with Ethernet and that IEEE 802.11a achieves a higher throughput with a larger packet size. The third reason is that beyond the point of saturation (0.27) with IEEE 802.11a more and more rt-VBR are discarded freeing capacity to carry ABR packets so that the ABR throughput remains high on cost of rt-VBR traffic. At a heavy saturation (0.4), the ABR throughput of W-CHAMB decrease a little due to the interruptions in favor of rt-VBR traffic. Fig. 13 shows the CDF of the rt-VBR service of W-CHAMB and IEEE 802.11a under various traffic loads. For W-CHAMB, the delay distribution of the rt-VBR service is still under control even under a heavy overloaded condition (0.5). At the traffic load of 0.25, the delay distribution of rt-VBR traffic is almost the same as that without any ABR traffic (0.12). With a higher traffic load from 0.34 to 0.50, the packet delay increases several millisecond because the probability that a station cannot find a free channel for a rt-VBR burst at its arrival increases. Several milliseconds are necessary to interrupt the transmission of an ABR packet train to free a channel for the rt-VBR traffic. IEEE 802.11a instead is not able to differentiate rt-VBR and ABR traffic. At a very low traffic load condition, rt-VBR service has a good delay performance. But the delay performance degrades rapidly with a increasing traffic load. With a moderate traffic load of 0.25, the delay performance of the rt-VBR service is no longer acceptable. Fig. 12 and Fig. 13 reveal that IEEE 802.11a cannot well support a rt-VBR service in a multihop environment, whereas W-CHAMB is able to guarantee QoS even under a high traffic load. Fig. 14 shows the CDF of the ABR traffic. The delay distribution of ABR service is dependent significantly on the traffic load for both, W-CHAMB and IEEE 802.11a.

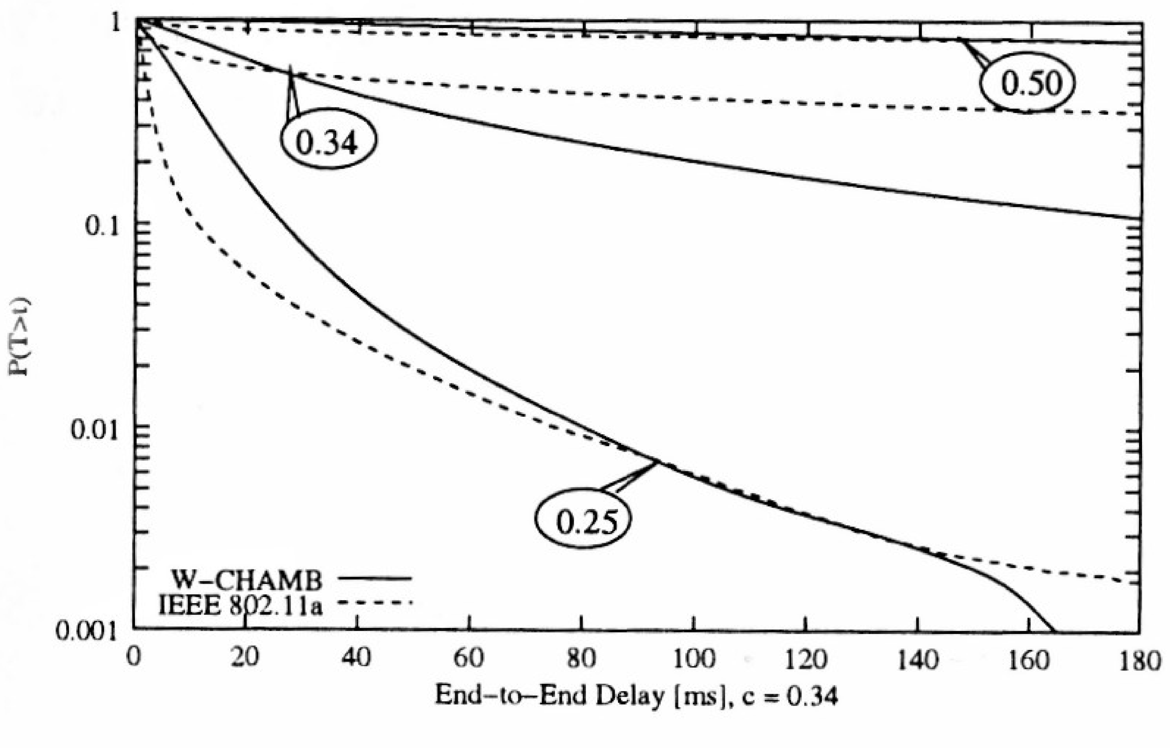

Figure 14: CDF of ABR traffic at c = 0.34

6 Conclusions

The traffic performance in H/2, IEEE 802.11 and W-CHAMB is compared under different network scenarios by stochastic computer simulation. H/2 with its central control has the best traffic performance in fully connected small scale networks. But H/2 appears not to be suited for operation as a self-organising multihop network.

IEEE 802.11 uses decentral control and is suited for multihop self-organising networks. However, simulation results reveal that DCF is inefficient for short to medium size packets. Moreover, DCF has no means to support QoS for real-time services in multihop network environment and PCF is not applicable there.

W-CHAMB with its channel-oriented decentrally controlled MAC protocol is able to guarantee ATM-like QoS for rt-VBR services in a self-organising multihop network. In addition, even with realistic Ethernet packet sizes, W-CHAMB achieves much higher efficiency than IEEE 802.11a. The W-CHAMB MAC protocol appears to be the best suited solution for self-organising broadband multihop networks.

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