ON THE MAC PERFORMANCE OF SELF-ORGANIZING BROADBAND MULTIHOP MULTIMEDIA WIRELESS NETWORKS

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Abstract –

This paper evaluates and compares MAC (Medium Access Control) performance of ETSI HiperLAN/2 (H/2), IEEE 802.11 and W-CHAMB using stochastic computer simulations. H/2 adopts a fully centralized scheduler-oriented MAC approach that has best traffic performance in fully connected small networks. IEEE 802.11 uses a packet-oriented CSMA/CA MAC solution that is inefficient for short to medium packets, and can not guarantee QoS in a multihop networking environment. COMNETS W-CHAMB supports high performance real time traffic services in multihop networks and achieves a high efficiency for short PDU trains.

I. INTRODUCTION

Self-organizing broadband multihop multimedia wireless networks with QoS guarantee are emerging as one of the key issues of the 4G (4th generation) wireless communications. New multimedia services accessible via the Internet is strongly driving the demand for broadband wireless networking. Due to the high radio capacity required by the broadband transmission, broadband wireless networks can only be operated at the frequency spectrum above 5 GHz. Since the 5 GHz band has been opened for the personal communication as license-exempt frequency spectrum, it has been the most promising frequency spectrum for the broadband wireless networking. In Europe, HiperLAN 2 was standardized by ETSI project BRAN in April 2000. In the U.S., Standard IEEE 802.11a has been developed to extend the IEEE 802.11. Both systems, ETSI HiperLAN 2 and IEEE 802.11a, operate in the 5 GHz frequency band and provide data rates up to 54 Mb/s.

But as 5 GHz or higher frequencies have very unpredictable propagation characteristics and very limited ability to penetrate obstructions, the communication zone is strongly deformed and there exists a severe shadowing effect. At most cases, communication is only possible between wireless stations with line of sight connections. Multihop transmission must be considered to overcome the showing effect and to achieve a reasonable communication coverage.

Self-organizing broadband multihop multimedia wireless network with QoS guarantee will find many applications soon. They can be used as broadband wireless Internet access networks for hot-spots, such as airports, railway stations, trading fairs, campuses, commercial areas and dense residence areas *etc.*. They can also be used as adhoc networks without any AP for military operations, disaster reliefs, news conferences and musical events. In addition, the need to exchange computer data, such as digital music/video, or to play a computer game anywhere at anytime among any people will be ever increasing. Another important application is wireless LAN (WLAN) for distributed wireless computing in research laboratories, large companies and factories.

The most challenging task to realize a self-organizing broadband multihop multimedia wireless network with QoS guarantee is to design an efficient MAC protocol. A self-organizing network prefers decentralized organization. The responsibilities of organizing and controlling should be fully distributed among wireless stations themselves. But a central controller seems necessary to realize statistical multiplexing of bursty traffic of multimedia applications and to meet different QoS requirements.

This paper evaluates and compares three possible MAC candidates for self-organizing broadband multihop multimedia wireless networks with QoS guarantee. The MAC protocol of IEEE 802.11 is examined at first to see whether it can meet our design objectives. Then, we discuss the MAC protocol of ETSI HiperLAN 2 standard. H/2 MAC protocol adopts a fully centralized approach. Finally, we

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propose a new MAC protocol, called W-CHAMB (wireless channel oriented ad-hoc multihop broadband) MAC protocol. These three MAC protocols represent three fully different approaches to share a common wireless channel among wireless stations (WSs).

II. IEEE 802.11

The access scheme of IEEE 802.11 consists of DCF (distributed coordination function) and PCF (point coordination function)[4]. DCF, based on the carrier sense multiple access with collision avoidance (CSMA/CA), is the fundamental mechanism of the medium access control (MAC). DCF has two mechanisms to access the medium, namely the basic access mechanism and the RTS/CTS mechanism. Both mechanisms use an exponential backoff scheme and an immediate transmission of a positive acknowledgment (ACK) by the receiving station. DCF can work without any AP and can realize multihop communication.

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. 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. 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.

The limitations of DCF to be used in self-organizing broadband multihop multimedia wireless networks are follows:

1. The transmission of data frame in IEEE 802.11 is packet-oriented. An explicit ACK is used to acknowledge the successful reception of the data frame. This results in inefficiency for the transmission of short packets, such as ATM cells.
2. The hidden station problem cannot solved by the RTS/CTS mechanism completely. In a multihop environment, there exist many cases at which hidden stations cannot receive RTS/CTS packets [5].
3. DCF does not support provision of different QoS requirements to different services. It cannot provide any QoS guarantee for real time services.
4. To realize collision avoidance, DCF uses backoff process. This backoff process increases the protocol overhead. The higher the data rate in the air interface, the more significant this overhead will be.

III. ETSI HIPERLAN/2

In HiperLAN 2, on the other hand, a fully centralized MAC protocol is specified. A central controller assigns the radio resources within the HiperLAN/2 MAC frame. The assignment of resources may change from frame to frame. The fixed length HiperLAN/2 MAC frame ($t_{frame} = 2ms$) consists of three major phases. The broadcast phase is used to transport the control information. The downlink, directlink and uplink phase is used to transport data PDUs between the central controller and the WSs or between WSs. The random access phase is used for the initial access to the network, for handover indication and for requesting radio resources.

Using a centralized solution like H/2 MAC protocol for self-organizing broadband multihop multimedia wireless networks may suffer from the following inherent problems:

1. To be self-organizing, most wireless stations should have an in-built central control function. As a central controller in a broadband wireless network needs very high computing capacity, the hardware requirements on the wireless stations increase dramatically.
2. The network will be complicated and vulnerable. The failure or departure of the selected central controller will cause temporary chaos in the whole network.
3. Direct mode and multihop communication cannot be realized efficiently as communication is possible only under a central control.
4. The scarce frequency spectrum cannot be used efficiently. Neighboring central controllers must use different frequencies. Dynamic channel allocation which is inherent in decentralized networks is not easy to perform.
5. A wireless station may not be able to associate because it may not be able to receive the information from the central controller or the central controller cannot hear this wireless station.

IV. COMNETS W-CHAMB

W-CHAMB, an idea developed at ComNets, Aachen University of Technology, achieves statistical multiplexing of bursty traffic through packet reservation. The most significant feature of W-CHAMB is that it meets QoS demands for different services and realizes statistical multiplexing of bursty traffic in a fully distributed and efficient manner [5, 6, 7, 12, 13]

In comparison with HiperLAN 2, the advanced features of W-CHAMB MAC protocol are its multihop ability and decentralized control. The centralized MAC solution of HiperLAN 2 will reach its limitation soon if users in 5-6 GHz license-exempt frequency spectrum increase. In comparison with IEEE 802.11, W-CHAMB achieves a much higher network efficiency for short to medium packets. More importantly, the DCF of IEEE 802.11 has no means to support QoS of real time services. W-CHAMB can be viewed as a convergence of HiperLAN 2 and IEEE 802.11. It takes the advantages of IEEE 802.11 and HiperLAN 2, but overcomes their shortcomings.

V. PERFORMANCE EVALUATION

Intensive stochastic computer simulations are used to evaluate and compare the three MAC protocols. The physical layer of W-CHAMB uses the same OFDM modulation schemes as standardized for IEEE 802.11a [3] and H/2 [1]. The size of a data packet sent in one slot with 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.

Traffic performance in a fully connected network

Consider a network that consists of an AP serving a video stream download (MPEG) and a duplex voice connection (N-ISDN), and eight WSs exchanging Ethernet packets with their direct neighbor WSs 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 [10][11].

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 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.1 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. 2.

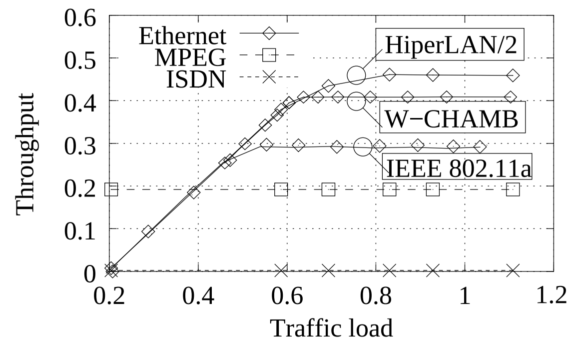

Figure 1: One hop throughput performance

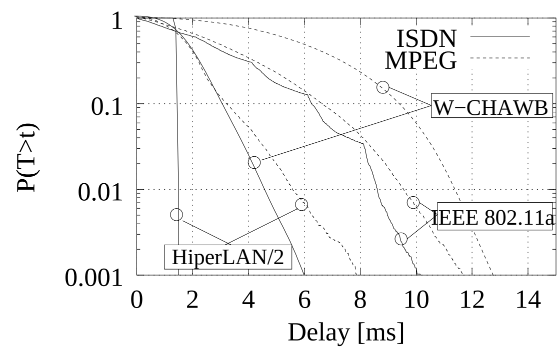

Figure 2: CDF of MPEG and N-ISDN at high traffic load conditions

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.

Multihop traffic performance

To study the traffic performance in a multihop wireless access scenario, a 5x5 square grid network with 24 WSs and one AP is used, see Fig. 3. The network 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. To evaluate the network efficiency and the grade of the QoS support of real time traffic, we study the network shown in Fig. 3 with a connectivity of 0.34. 25 end-to-end virtual connections (VCs) are established permanently during the simulation. Five rt-VBR end-to-end connections between the AP and 5 WSs are established to simulate the download real time video stream. The resulted mean hop of the five rt-VBR end-to-end connec-

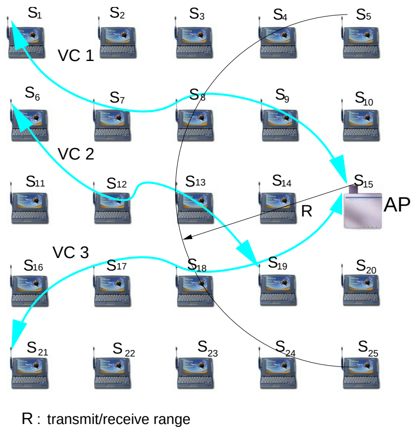

Figure 3: Multihop wireless access scenario

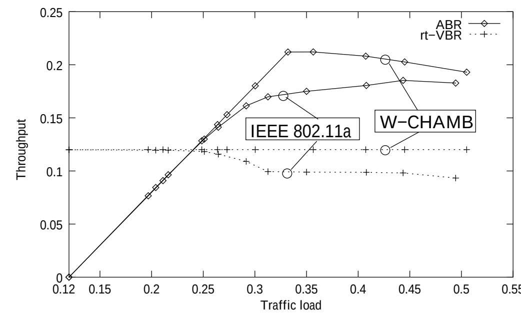

Figure 4: Throughput performance at c = 0.34

tions is 1.6 hop. Another 10 WSs receive ABR packets from the AP, resulting in 10 downlink ABR end-to-end connections. 5 uplink ABR end-to-end connections are established to transport ABR packets from five WSs to the AP. Another five WSs randomly select a WS as ABR traffic sink, resulting in 5 directlink end-to-end connections. The resulted mean hop of the all ABR end-to-end connections is 1.9 hop. The Min-hop routing algorithm is used to establish a multihop end-to-end connection. 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. ABR traffic uses realistic packet sizes read from an Ethernet trace file [11]. The interarrival time of Ethernet packet read from the trace file has been varied to model different loads. The transmission rate of 24 Mb/s is used for both systems, W-CHAMB and IEEE 802.11a.

The packet error rate depends on the carrier-to-interference ratio (C/I) and packet size. The results of [9] 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 urban environments is $\alpha = 4$.

Multihop traffic performance with W-CHAMB and IEEE 802.11a is shown in Fig 4, 5 and 6. The unique feature of W-CHAMB is QoS guarantee for real time traffic in a multihop access scenario without any central control. Fig.4 shows that the prioritized rt-VBR service with W-CHAMB is served with the same throughput (0.12) under all load conditions, whereas the throughput of rt-VBR service with IEEE 802.11a decreases with an increasing traffic load since a rt-VBR packet is dropped if its delay exceeds 30 ms. The maximum throughput of the ABR service is 0.21 with W-CHAMB at the traffic load of 0.33, including 0.12 of rt-VBR traffic. After that, the network is saturated and the throughput of the ABR service decreases a little as ABR RCCs are frequently interrupted and resumed later to free a channel for rt-VBR traffic at a saturation condition. IEEE 802.11a, however, approaches saturation at a lower traffic load of 0.26. After that, the throughput of the ABR service with IEEE 802.11a increases a little as many rt-VBR packets are discarded freeing capacity to carry more ABR packets. The throughput of the rt-VBR service with IEEE 802.11a does not decrease proportionally after the load of 0.31 as a WS or the AP transports rt-VBR packets at first if it has rt-VBR packets and ABR packets at the same time. It can be seen in Fig. 4 that the maximum throughput of both ABR and rt-VBR traffic (0.33) with W-CHAMB is much higher than that with IEEE 802.11a (0.26) at the multihop access network. It appears that the channel-oriented W-CHAMB is much more efficient than the packet-oriented IEEE 802.11a. The maximum throughput (0.33) with W-CHAMB is limited due to the multihop transport of PDUs, PDU headers and the physical layer overhead.

Fig. 5 and Fig. 6 show the CDFs (complementary distribution functions) of the rt-VBR service with W-CHAMB and IEEE 802.11a, respectively. The delay distribution of the rt-VBR service with W-CHAMB is still under control even under a heavy overloaded condition (0.51). With an increasing traffic load from 0.21 to 0.51, the rt-VBR packet delay increases several milliseconds because the probability that a station cannot find a free channel for a rt-VBR PDU train at its arrival increases with an increasing load. Several milliseconds are necessary to interrupt an ABR RCC to free a TCH for the rt-VBR traffic. IEEE 802.11a instead is not able to differentiate rt-VBR and ABR traffic. At a low traffic load condition (0.20), rt-VBR service has an acceptable delay performance. But the delay performance degrades rapidly with an increasing traffic load. With a moderate traffic load (0.25), the delay performance of the rt-VBR service is no longer acceptable. Fig. 4 and Fig. 6 reveal that IEEE 802.11a

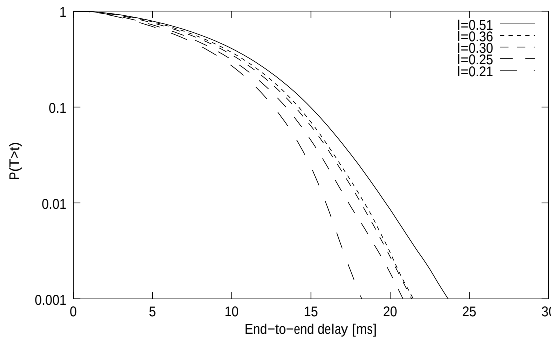

Figure 5: CDF of rt-VBR traffic with W-CHAMB at c = 0.34

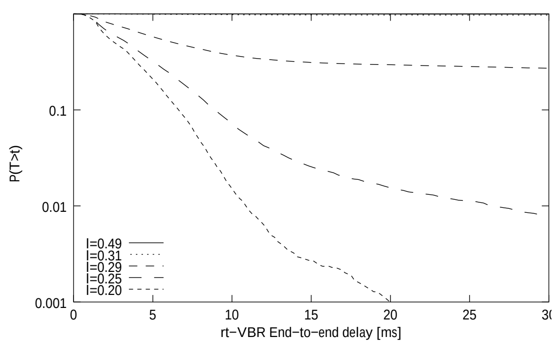

Figure 6: CDF of rt-VBR traffic with IEEE 802.11a at c = 0.34

cannot support rt-VBR service in a multihop access network, whereas W-CHAMB is able to guarantee QoS for rt-VBR service even at a heavy overloaded situation.

VI. CONCLUSIONS

The traffic performance with H/2, IEEE 802.11 and W-CHAMB is compared using stochastic computer simulations. 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-organizing multihop network.

IEEE 802.11 uses decentral control and is suited for multihop self-organizing 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-organizing 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 MAC solution for self-organizing broadband multihop multimedia wireless networks.

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