Design Issues of Self-Organizing Broadband Wireless Networks*

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Abstract

Design issues of self-organizing broadband wireless networks are examined in this paper. As centralized solutions suffer from many inherent disadvantages, the responsibilities of organizing and controlling self-organizing networks should be fully distributed among wireless stations themselves. W-CHAMB (Wireless CHannel oriented Adhoc Multihop Broadband) ideas that meet QoS demands for high performance services and realize statistical multiplexing of bursty traffic in a fully distributed and efficient manner are described in detail. The superiority of the performance of the W-CHAMB network can be seen in comparison with that of packet-oriented IEEE 802.11 WLAN. The hidden station problem is completely resolved by means of the energy signal (E-signal) solution. The performance gain of the E-signal solution over the RTS/CTS mechanism is evaluated through computer simulation. Finally, the effect of network connectivity on the traffic performance is discussed.

1 Introduction

New multimedia services accessible via the Internet are strongly driving the demand for residential and commercial broadband wireless networking. Due to the high bandwidth required by broadband transmission, broadband wireless networks can only be operated in the frequency spectrum above 5 GHz. Since the 5-6 GHz band has been opened for the personal communication as license-exempt frequency spectrum, it has been the most promising frequency spectrum for broadband wireless networking. In Europe, Hiperlan Type 2 (H/2) was Standardized by ETSI project BRAN in April 2000. In the U.S., Standard IEEE 802.11a was developed in 1999 to extend the IEEE 802.11 standard. Both systems, ETSI H/2 and IEEE 802.11a, operate in the 5 GHz frequency band and provide transmission data rates up to 54 Mb/s [1] [2].

Based on the observation that 5 GHz or higher frequencies have very unpredictable propagation characteristics and very limited ability to penetrate an obstruction, the communication range of broadband wireless networks is strongly limited and there will exist severe shadowed areas. In most cases, communication is only possible between wireless stations with line of sight connections. Therefore, multihop transmission should be considered to overcome these limitations and to achieve a reasonable communication coverage. A self-organizing network with multihop transmission ability will be best suited to be operated in such a networking environment.

Since a self-organizing network can work without any preexistent infrastructure, it can be rapidly deployed. This feature is especially beneficial for temporary application scenarios, such as short term events, extension of the radio coverage of fixed infrastructure radio networks, disaster relief and military applications. Meanwhile, such a network is very reliable as failure or departure of some wireless stations will not cause the failure of the whole network. Due to the simplicity, flexibility and low cost to deploy a self-organizing network, the interest in such kind of networks will be increasing.

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2 Centralized vs. Decentralized

It seems that self-organizing means that no central control will be used in the network. So a self-organizing network should naturally be decentralized. This is fully true as long as high performance multimedia must not be supported. The controversy whether a self-organizing broadband wireless network should be controlled in a centralized or decentralized way arises due to the consideration that provision of QoS requirements may be more easily realized by a central controller. Based on this consideration, many researchers have developed algorithms to select central controllers in a self-organizing environment. With a simple network topology, in which a central controller can be optimally selected and the other wireless stations can successfully receive the control information from the central controller, the centralized self-organizing network may function well. But in most cases, no matter how good the selection algorithm is, a centralized solution suffers from the following inherent problems:

(1) To be self-organizing, most wireless stations should have a in-built central controller 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 control of a central controller.

(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.

As the centralized solution for self-organizing broadband wireless networks suffers from the limitations described above, we are sure that the best way for self-organizing broadband wireless networks is still the decentralized solution. The responsibilities of the organizing and controlling of self-organizing networks should be fully distributed among the wireless station themselves. Every wireless station decides by itself when and how to send its information according to predetermined algorithms and protocols.

As we decided to adopt the decentralized solution, we face another challenge, that is, how to realize QoS guarantee in a fully distributed broadband wireless network.

Actually, some efforts have been made to support QoS in a fully distributed network. In ETSI Standard Hiperlan Type 1 (H/1), a channel access protocol called Elimination Yield-Non-Preemptive Priority Multiple Access (EY-NPMA) which can support delay-bounded service has been specified [3]. But H/1 has not been accepted by the market because it suffers from the following problems:

(1) The EY-NPMA protocol does not solve the hidden station problem. As the performance of a self-organizing network degrades substantially due to hidden stations, a solution to the hidden stations problem must be found.

(2) The transmission of information in H/1 is packet-oriented. Here, packet-oriented transmission means that the duration of medium occupation is according to the packet length. The network throughput is extremely low for short packets, such as ATM cells, because of the large protocol overhead.

(3) The ability to support QoS is very limited. It is not possible to support high performance multimedia in H/1.

It is obvious that H/1 cannot meet the requirements of self-organizing broadband wireless networks.

3 Packet-oriented vs. Channel-oriented

3.1 The Packet-oriented solution: IEEE 802.11

Due to the worldwide great success of Ethernet, the packet-oriented CSMA (Carrier Sense Multiple Access) protocol is pervasive in the area of LAN. So the WLAN standard IEEE 802.11, viewed as a wireless extension of Ethernet, has also adopted the packet-oriented CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) access scheme [4]. A high speed physical layer in the 5 GHz Band, called IEEE 802.11a, has also been specified as a supplement to IEEE 802.11. The data rates of IEEE 802.11a will be up to 54 Mb/s [2].

Although the DCF (Distributed coordination function) of IEEE 802.11 is fully decentralized and self-organizing, it is not, however, suitable for self-organizing broadband wireless networks because of its inefficiency and no means to guarantee QoS.

The success of Ethernet is due to its simplicity. The throughput of CSMA/CD protocol in Ethernet can achieve a throughput of 82%. The increasing bandwidth requirements have been met by the high-speed Ethernet of 100 Mb/s and 1 Gb/s. IEEE 802.11 WLAN, however, has a different transmission medium. It is impossible for IEEE 802.11 to apply CSMA/CD because the sending station cannot detect any ongoing collision. So IEEE 802.11 can only use a CSMA/CA protocol. To achieve collision avoidance (CA), a large protocol overhead, such as backoff, is necessary. In addition, the existence of hidden stations in wireless environments makes the CSMA-like protocol very inefficient [8]. To overcome this problem, IEEE 802.11 has specified the RTS/CTS mechanism that increases the protocol overhead. It is worth mentioning that RTS/CTS cannot solve the hidden station problem completely (see Section 4). Moreover, one of the main advantages of the packet-oriented CSMA protocol, namely that the transmission of large packets can achieve high efficiency, is no longer valid in the wireless environment because the packet error probability will be higher for larger packets. Assume that the packet error rate (PER) of a short packet is 3 %, then the PER of a large packet of 10 short packets length will be $1 - (1 - 0.03)^{10} = 26\%$, which is no longer acceptable. So large packets have to be fragmented to short packets to achieve sufficient transmission reliability. Such a fragmentation will increase the overhead.

In our research, we have found that provision of QoS requirements of high performance multimedia applications in a packet-oriented self-organizing wireless network appears to be impossible. The current attempt of IEEE 802.11 to extend the DCF to support QoS guarantee will suffer from the same problems as that of H/1 described in Section 2.

3.2 The Channel-oriented solution: W-CHAMB

Inspired by the GPRS and DECT concepts, we developed a channel-oriented solution - W-CHAMB (Wireless CHannel-oriented Ad-hoc Multihop Broadband) networks - 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) [9]. It differs from

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 demands for different services and realizes statistical multiplexing of bursty traffic in a fully distributed and efficient manner.

3.2.1 W-CHAMB channel access structure

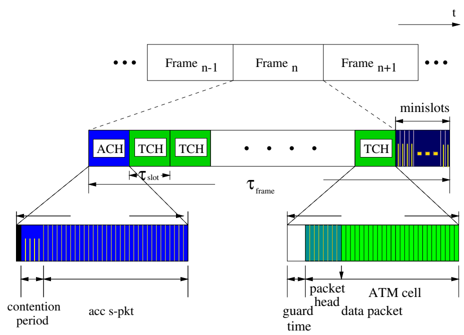

Fig. 1: W-CHAMB Access structure

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.1. All wireless stations (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. The first slot of the frame is 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 one data packet transmission per frame. Each data packet has a user data unit, such as an ATM cell, and a packet header containing information, such as packet identifier, sequence number, time information, etc., see [5].

At the end of the frame a number of minislots follow. Each minislot is associated with a TCH. If the TCH shall stay reserved, the receiving WS sends an energy signal (E-signal) on the corresponding minislot. The introduction of minislots may reduce the time available for message transmission. However, each minislot carries only a single on-off pulse of the unmodulated carrier, so that the related overhead is generally quite small. Moreover, as we use the same kind of E-signals to realize the distributed transmit priority, this solution does not increase hardware complexity. The E-signal is transmitted on the carrier frequency, so that the detection delay is negligible. The performance gain of this solution is evaluated in Section 4.

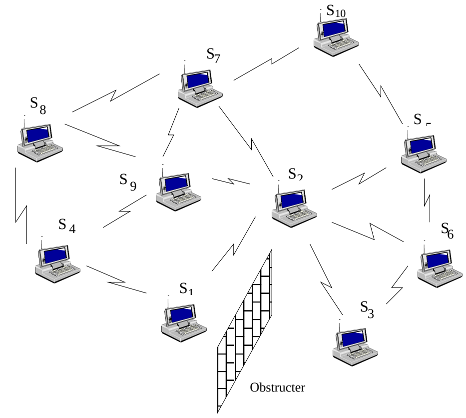

Fig. 2: Self-organizing broadband wireless network

3.2.2 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. 2 and 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 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 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 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 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.

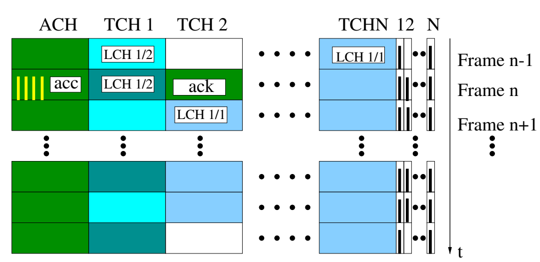

Fig. 3: Dynamic channel reservation

3.2.3 Distributed Access Priority

To be able to prioritize a real time VBR service, we define the QoS of real time VBR traffic services in terms of a maximum tolerable packet delay D_{max} and a packet dropping probability, P_{drop}. To give the more urgent information burst a higher access priority, we use a distributed access priority algorithm [6] [7].

3.2.4 Adaptive Back-off

In spite of using the distributed access priority, a collision on the ACH may happen if: (1) two WSs use the same priority; (2) contending WSs are hidden to each other. To avoid repeated collisions, we use an adaptive back-off algorithm [6] [7].

3.2.5 ABR reservation interrupted on demand

ABR traffic is multiplexed with rt-VBR traffic in the air interface. To use bandwidth efficiently, ABR services will use bandwidth resources which are temporarily not used by VBR services. As WSs reserve LCHs in an uncoordinated manner, an algorithm is necessary to ensure that a rt-VBR burst can always find a free LCH before its access deadline and at the same time the free bandwidth can be efficiently used by the ABR service. For that purpose any station receiving a request to open a LCH for a rt-VBR service will interrupt an ongoing ABR transmission and allocate the LCH freed by this to the rt-VBR service requested.

For the ABR traffic, the available bandwidth resources should be shared fairly among the WSs and should be used efficiently. On the one hand, it should be avoided that a WS reserves a LCH for a long time while other WSs may have no opportunity to send any ABR traffic. On the other hand, it should also be avoided that a WS is not allowed to transmit ABR traffic continuously even though there are enough free LCHs. To deal with this problem, a WS must check the channel occupancy situation at the end of each ABR burst transmission to evaluate the system traffic load. If the spectrum is highly loaded, the WS must back off for some time before it is allowed to apply for a LCH for ABR traffic again.

3.3 Performance comparison

Compared to the packet-oriented IEEE 802.11, the channel-oriented W-CHAMB LAN has the following advantages: (1) It achieves high network efficiency. (2) It supports rt-traffic in a fully distributed manner. With realistic Ethernet packet sizes with a mean of 434 bytes for an IEEE 802.11 WLAN at the transmission rate of 24 Mbit/s, the superiority of the performance of W-CHAMB can be seen from the simulation results in [11].

4 The hidden station problem

Hidden stations may result in extreme inefficiency in self-organizing wireless networks. A hidden station is a station that cannot sense the transmission of the sending WS, but will cause interference to the receiving WS if it transmits. Hidden stations can be caused by obstruction, see, Fig. 2. Assume that S_2 is receiving data from S_1. But S_3 cannot sense the transmission of S_1 because of the obstructer. If S_3 transmits at the same channel as used by S_1, S_2 will be interfered. S_3 is a hidden station in this case. Hidden stations may be caused by the multihop environment. Even if there is no obstructer, hidden stations can result from the different distances among wireless stations. Assume that S_2 is receiving from S_1 again. As S_5 is out of the detection range of S_1, it cannot sense the transmission of S_1. So S_5 is a hidden station which may cause interferences to S_2. Hidden stations may degrade the network performance substantially. There are two basic approaches to solve the hidden station problem:

(1) The busy tone solution was firstly proposed in [8] to combat hidden stations in CSMA systems. A busy tone signal is sent by the receiving station on a narrow band channel to make a hidden station aware of an ongoing transmission and prevent it from transmitting and interfering. The limitation of the busy tone solution is the need of a separate channel, the need of additional hardware for the receiver to transmit the busy tone while receiving on the data channel and the large delay of detecting the busy tone in a narrow band channel. The last limitation makes it impossible to use the busy tone solution in broadband wireless networks.

(2) The RTS/CTS (request to send/clear to send) mechanism as specified in IEEE 802.11 is able to combat hidden stations. A station that intends to send a data packet sends a RTS packet to the receiver. After reception, in turn, the receiver sends a CTS packet to indicate it is ready to receive data. Other stations that receive the RTS and/or CTS packet will defer their access for a period of time according to the transmission duration information contained in the RTS/CTS packets. The goal of the RTS/CTS mechanism is that hidden stations should receive the CTS packet and would cooperate then. But the RTS/CTS mechanism does not solve the hidden station problem completely. Some cases remain where hidden stations cannot receive the CTS packet. For example, see Fig. 2, S_{10} cannot receive the CTS packet from S_2 because it is out of the decode range of S_2. But S_{10} can cause interference to S_2 as S_{10} is still in the interference range of S_2. The interference range is usually much larger than the decode range. In some cases, even though a station is in the decode range of the receiver, it may not be able to receive the CTS packet because of the interference of other stations. For example, S_9 is in the decode range of S_2. But if S_8 is sending while S_2 transmits the CTS packet, S_9 cannot receive the CTS of the S_2. So S_9 may access the channel after S_8 ended the transmission, which causes interference to S_2.

In the W-CHAMB network, the hidden stations problem is solved completely through E-signals transmitted on minislots, see Section 3.2. Although the introduction of minislots does increase the system overhead, the performance gain of using E-signal can be derived from Fig. 4. The network throughput is defined as the number of successfully transmitted data packets divided by the simulated time (counted in slots). The simulated network consists of 20 WSs with a connectivity of 0.58, see Section 5. The length of a minislot is assumed 10% of a normal slot. ABR traffic and rt-VBR traffic are mixed, each 50 %. The packet error rate is assumed to be 3 %. If the E-signal is not used, all WSs that receive an *ack s-pkt*, see Section 3.2.2, keep silent for the duration of the transmission so that the *ack s-pkt* has a function similar to CTS packets [11]. So the performance resulting in Fig. 4 indicates that the RTS/CTS mechanism is not enough to solve the hidden station problem.

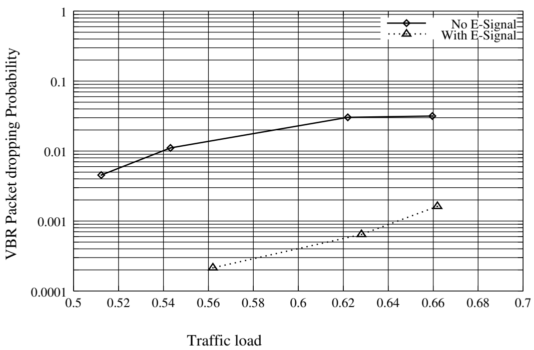

Fig. 4: VBR packet dropping probability, c = 0.58

5 Impact of network connectivity

To study the impact of the network connectivity on the traffic performance, we consider a 5x5 square grid network with 25 wireless stations. 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 a fully connected network has a connectivity of 1.

The packet error rate depends on the carrier-to-interference ratio (C/I). We assume the same physical layer as defined for H/2 and use the results of [10] concerning the relation between the C/I and the packet error rate. 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 $\alpha = 4$.

Each wireless station produces a Poisson traffic stream and randomly selects another station as its traffic sink. The burst length of traffic is geometrically distributed with mean of 30 packets, each sent in one time slot. The packet size is 54 bytes. The interarrival time of bursts is negative exponentially distributed. The mean value of the interarrival time is adjusted to meet the traffic load to the whole network. In our simulation, we decided to drop packets that have exceeded a delay of 15000 slots, e.g., 300 msec.

Fig. 5 and 6 show the impact of the network connectivity on the network throughput and the mean end-to-end packet delay. With a connectivity of 0.93, the network has the highest traffic performance. There, the throughput is increased linearly with the traffic load until a traffic load of about 0.71, where the network becomes saturated. Many packets are dropped then due to large delay. At the traffic load of 0.84, the network throughput declines by about 8% owing to changes of lengths of the connections counted in hops. It can be seen that the traffic performance is reduced with a smaller connectivity. With a connectivity of 0.24, the network is saturated at a traffic load of 0.31. The strong decline of the throughput at the load of 0.38 is due to a increased mean number of hops of each connection still served. The mean delay versus traffic load at different connectivities is shown in Fig. 6. It can be seen that if the network is lightly loaded, the mean delay increases slowly with increased traffic load. The mean delay increases significantly if the network approaches saturation. With $c = 0.93$, the mean delay indicates saturation at a traffic load of 0.71. Under higher traffic load, the mean delay increases further, but with a reduced slope since packets with large delay are dropped there and are not counted in the mean delay. The significant change of the packet delay when the network approaches saturation can also be seen from the complementary distribution functions (CDF) of end-to-end packet delay with the different traffic loads at the connectivity of 0.93, see Fig. 7 . It can be seen that there are two groups of delay distribution curves. One comprises distributions with the traffic loads under 0.71. The other those with traffic loads above 0.71. As the network is lightly loaded under traffic loads of 0.64, data packets experience smaller delay. Above traffic loads of 0.71, the network is saturated. So data packets experience larger delay. All the curves decline at the delay of about 15000 slots (300 ms) dramatically since packets that exceed that delay are dropped at the source stations. The delay of dropped packets is not considered in the curves. Some packets may experience a delay larger than 15000 slots as packets that have left the source station are not dropped in the relay stations.

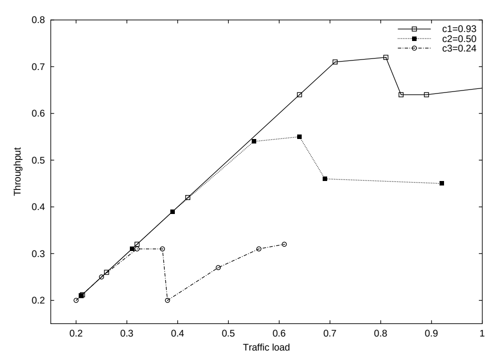

Fig. 5: Throughput vs. traffic load

Although frequency spatial reuse is possible in networks with a small connectivity and has been considered in our simulations, the system capacity is used up rapidly owing to the multihop transmissions needed for end-to-end

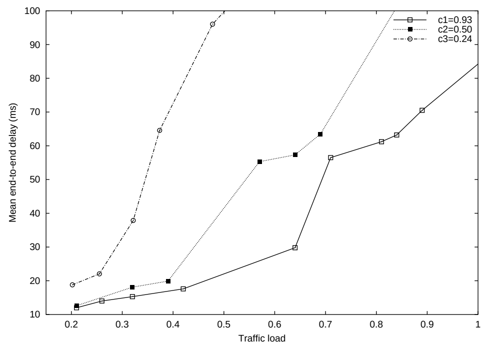

Fig. 6: End-to-end packet mean delay vs. traffic load

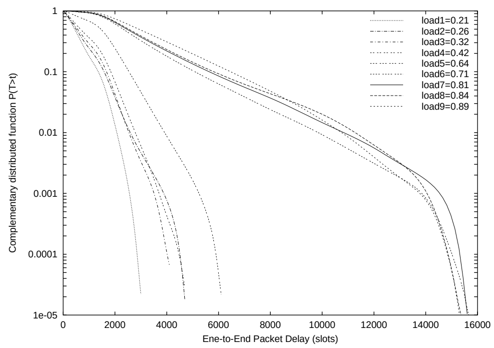

Fig. 7: End-to-end packet delay CDF, c=0.93

connections. The benefits of frequency spatial reuse in multihop networks is adverse to that of cellular networks that only use one hop per connection. It can be derived from the results presented that in multihop networks, frequency spatial reuse does not remarkably increase the network capacity. A comparison of the saturation throughputs of 0.71 and 0.31 under connectivities of 0.93 and 0.24 indicates that a factor of about 4 in connectivity does correspond to a factor of about 2.3 in saturation throughput. This is due to the frequency reuse.

6 Conclusion

We have presented some ideas and solutions for the design of self-organizing broadband wireless networks. We have shown that QoS cannot be guaranteed to high performance multimedia applications in a packet-oriented self-organizing wireless network.

Channel oriented packet transmission has proven to be appropriate to control QoS in a self-organizing wireless network. The maximum number of hops of a connection should be limited to achieve a reasonable traffic performance. Another lesson we learned is that a network with decentralized control is best suited for the operation of a self-organizing broadband wireless network. It can expected that the centralized design of H/2 phase 1 will reach its limitations soon if the number of users in the 5-6 GHz unlicensed frequency spectrum increases. So an extension of H/2 to a fully decentralized self-organizing network appears to be necessary in the future.

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8 Biographies

Bangnan Xu

Bangnan Xu received his B.S. and M.S. degrees in electrical engineering from Dalian Maritime University, Dalian, China, in 1986 and 1989, respectively. From 1989 to 1996, he was a Lecturer on satellite communication and communications theory in Dalian Maritime University. Since 1996, he has been a research assistant at the chair of communication networks, Prof. Dr. Ing. B. Walke, Aachen Univ. of Technology, Aachen, Germany. His research interests include self-organizing wireless broadband networking, mobile communication protocols and queuing theory.

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Professor Walke received his Diploma and doctor's degree in Electrical and Communications Engineering in 1965 and 1975, both from the University of Stuttgart, Germany. From 1965 to 1983 he worked as a researcher and department head in various industrial companies, where he designed computer based communications networks and evaluated their traffic performance. 1983 he joined the Department of Electronics Engineering, FernUniversity of Hagen as a full professor for Dataprocessing Techniques. In 1990 he moved to Aachen University of Technology (RWTH) as a full professor for Communication Networks. Current research covers air-interface design, protocols, stochastic performance simulation and services of wireless and cellular radio systems. His research group currently counts 36 full-time scientists, mainly funded by third parties. His scientific work comprises more than 80 scientific papers and five textbooks, on modelling and performance evaluation of computer systems and communication networks. The latest book is Mobile Radio Networks, Wiley&Sons, New York 1999. Prof. Walke is member of ITG/VDE, GI and IEEE and has served as programme committee chairman of European conferences like EPMCC and EW.