Camera ready version for

Second ACM/IEEE International Conference on Wireless and Mobile Multimedia (WOWMOM'99)

August, 20., 1999, Seattle, Washington

Authors: Matthias Lott, Bernhard Walke

Title: **Performance of a Wireless Ad hoc Network Supporting ATM**

Address: Aachen University of Technology (RWTH)
Communication Networks (COMNETS)
Kopernikusstr. 16
52074 Aachen, Germany

Tel.: +49-241-805828

Fax.: +49-241-8888242

E-Mail: lott@comnets.rwth-aachen.de

www: http://www.comnets.rwth-aachen.de/~lott

Performance of a Wireless Ad hoc Network Supporting ATM

Matthias Lott
Communication Networks
Aachen University of Technology
D-52074 Aachen, Germany
Tel.: +49/241-805828
E-mail: lott@comnets.rwth-aachen.de

Bernhard Walke
Communication Networks
Aachen University of Technology
D-52074 Aachen, Germany
Tel.: +49/241-807913
E-mail: walke@comnets.rwth-aachen.de

ABSTRACT

A wireless ad hoc multihop network is introduced and protocols for the air interface are described and evaluated. The network nodes are assumed able to route connections according to the current radio connectivity of the network. The decentrally organized network can guarantee the bandwidth contracted to a connection (e.g. ATM connection) in a hidden station environment by means of contention-free data transmission for both, channel and packet switched services, based on real channel connections (RCCs). Channels are established and used for the duration of a so called train of data packets, released when the train ends and re-established when the next train arrives. Most efficient use of the spectrum capacity is provided by a mechanism for dynamic channel allocation to nodes and services. To guarantee availability of network capacity for the re-establishment of a connection, connection admission control is applied considering the overall interference situation and the current radio connectivity.
A performance evaluation of the proposed protocols is presented by means of a simulation study for example scenarios.

Keywords

Wireless LAN, Ad hoc, Multihop, Self-organizing, Hidden station, Dynamic Channel Allocation, Medium Access Control.

1 INTRODUCTION

Packet (e.g. ATM[1]) based radio communication has been intensively investigated. For data rates up to 2 Mbit/s at the frequency band of 2.4 GHz the standards IEEE 802.11 [12], and at 5.2 GHz with a max. data rate of 23.5 Mbit/s HIPERLAN[2]/1 [6], have been established, and improvements to reduce the collision probability in IEEE 802.11 have been proposed in [3]. These systems rely on the MAC[3] protocols carrier sense multiple access (CSMA) with collision avoidance (CA) and EY-NPMA[4], respectively, to assign transmission capacity on a packet basis to competing stations within a radio cell. The probabilistic nature of CSMA/CA is known to be unable to support real-time oriented traffic Furthermore, these systems suffer from large protocol overhead especially for short data packets, low bandwidth efficiency and no guarantee of quality of service (QoS).

Alternatively to a decentral control by the distributed coordination function (DCF), IEEE 802.11 optionally defines a centralized access mode (point coordination function, PCF) based on polling. Since the PCF cannot be operated simultaneously in neighbouring cells and since it requires an access point with specialized access functions implemented, it imposes severe constraints on the operation of wireless local area networks (LANs).

Besides the IEEE 802.11 supplement for the 5 GHz band [13] current proposals for MAC protocols for W-ATM systems at 5.2 GHz with net data rates up to 54 Mbit/s rely on the concept of nodes that centrally control the transmission of stations [1], [14]. The transmission of data on the up- and downlink under control of a central node is the easiest form of access control. These designs suffer from the fact that, for any packet (or sequence of packets), transmit capacity has to be

[1] Asynchronous Transfer Mode
[2] High Performance Radio Local Area Networks
[3] Medium Access Control
[4] Elimination Yield-Non-Preemptive medium access control, used in HIPERLAN/1

allocated on the uplink anew, requiring the successful reception of a random access packet at the node before the link capacity for the transmission of the packet can be allocated. Random access usually is based on a Slotted-Aloha or CA protocol where packets may collide. Alternatively, stations may use reserved so called polling slots to signal transmit requests to the central node collision free [4]. In wireless systems with packet based reservation of transmission capacity, it cannot be guaranteed that other central nodes in the vicinity of a given node do not allocate the same time slot to the stations under their control, since the future usage of the radio medium is impossible to predict by observing the current radio resources occupation. The situation of unpredictable interferences and dynamically changing capacity requirements are typical for ad hoc scenarios as depicted in Figure 1.

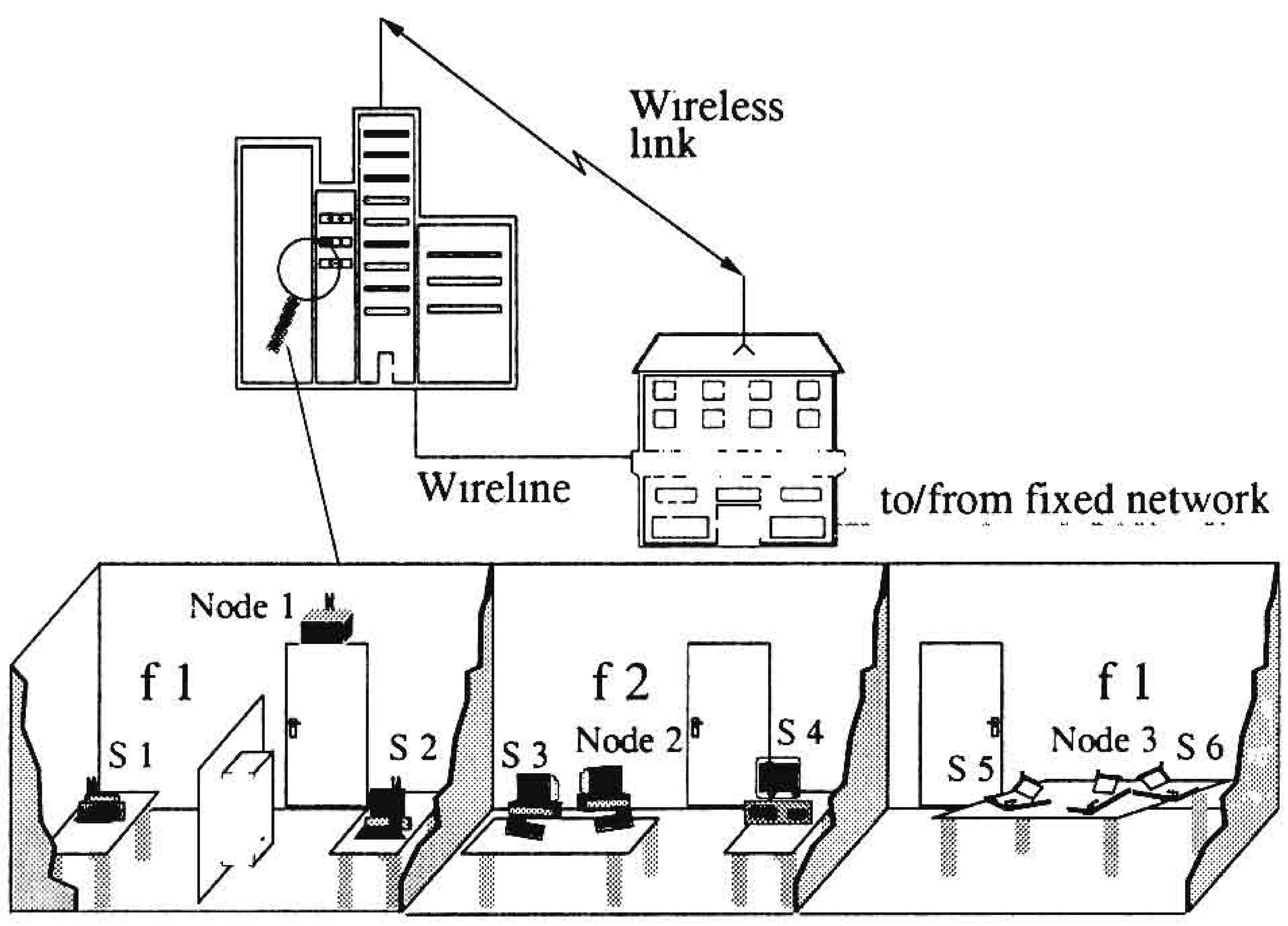

Figure 1: Ad hoc scenario with central control of stations S_i by nodes, where nodes use frequencies f_i; access to the fixed network is provided by a radio hop or by a wireline.

Assume node 3 uses the same frequency as node 1, since they have no radio contact, the stations that are under their control probably interfere as their radio connectivity is different.

2 DYNAMIC CHANNEL ALLOCATION AND REAL CHANNEL CONNECTIONS

Different from the protocols mentioned above the proposed network relies on dynamic channel allocation (DCA) and the concept of real channel connections (RCCs) [15]. No central control is used but all radio terminals (called nodes) decentrally acquire transmit capacity when needed and release it by simply not using it. DCA schemes are known to be extremely flexible and efficient with respect to the allocation of frequency and time channels to nodes. For point-to-point communication between nodes, RCCs are established, used and released, e.g. like in the DECT or PHS systems [5], [8]. An RCC provides capacity for collision-free transmission of packets, e.g., ATM cells, in slots of a framed TDMA system in a hidden station environment. To open a connection (RCC) by a node to the next node, the most silent channel is used. Therefore, each node maintains a local channel occupancy list of the total system's TDM-channels in terms of the Received Signal Strength Indicator (RSSI) measured at the node. After opening the connection, all other nodes in the receive range of the two nodes involved will recognize and respect the occupancy of the channel as long as they measure a defined level of signal strength. Time division duplexing (TDD) on the same frequency is used. Compared to frequency division duplexing (FDD), TDD has advantages since all nodes in the receive range of a node are able to detect the occupied channels without scanning the system frequency bands and no fixed duplexing space in the spectrum is required. Further, asymmetric communication can be better supported.

RCC based systems are potentially better suited to guarantee an agreed transmission capacity in an ad hoc environment than systems based on dynamic slot assignment [7] or random MAC protocols, due to the unpredictability of the random usage of the radio medium in the receive range of any node involved. Consequently, in Section 4 a concept for the wireless air interface is introduced that relies on the use of RCCs (see SAMA [2] and RNET [9]), and that is able to guarantee a negotiated QoS based on a spectrum-efficient connection admission control (CAC) (Section 6). Performance results of the ad hoc multihop radio network demonstrating its ability to guarantee the QoS are presented in Section 7.

3 WANET ARCHITECTURE

The reference model of the proposed wireless ad hoc network (WANET) is shown in Figure 2. Different from Figure 1 there is no central control node but only nodes in the network, able to route forward packets received according to virtual channel connections (VCC) established beforehand. A VCC defines an end-to-end connection with an agreed on quality of service over one or several hops. Nodes with reduced complexity that have no routing functionality can also participate in the network. Those nodes reduce the connectivity but behave like other nodes.

One version of the network is a radio access system providing standard ATM-Forum UNI/NNI interfaces at the terminal and network sides, respectively. Terminal adaptors (TA) contain the functions of radio modems and are used to bridge the wireless medium by means of

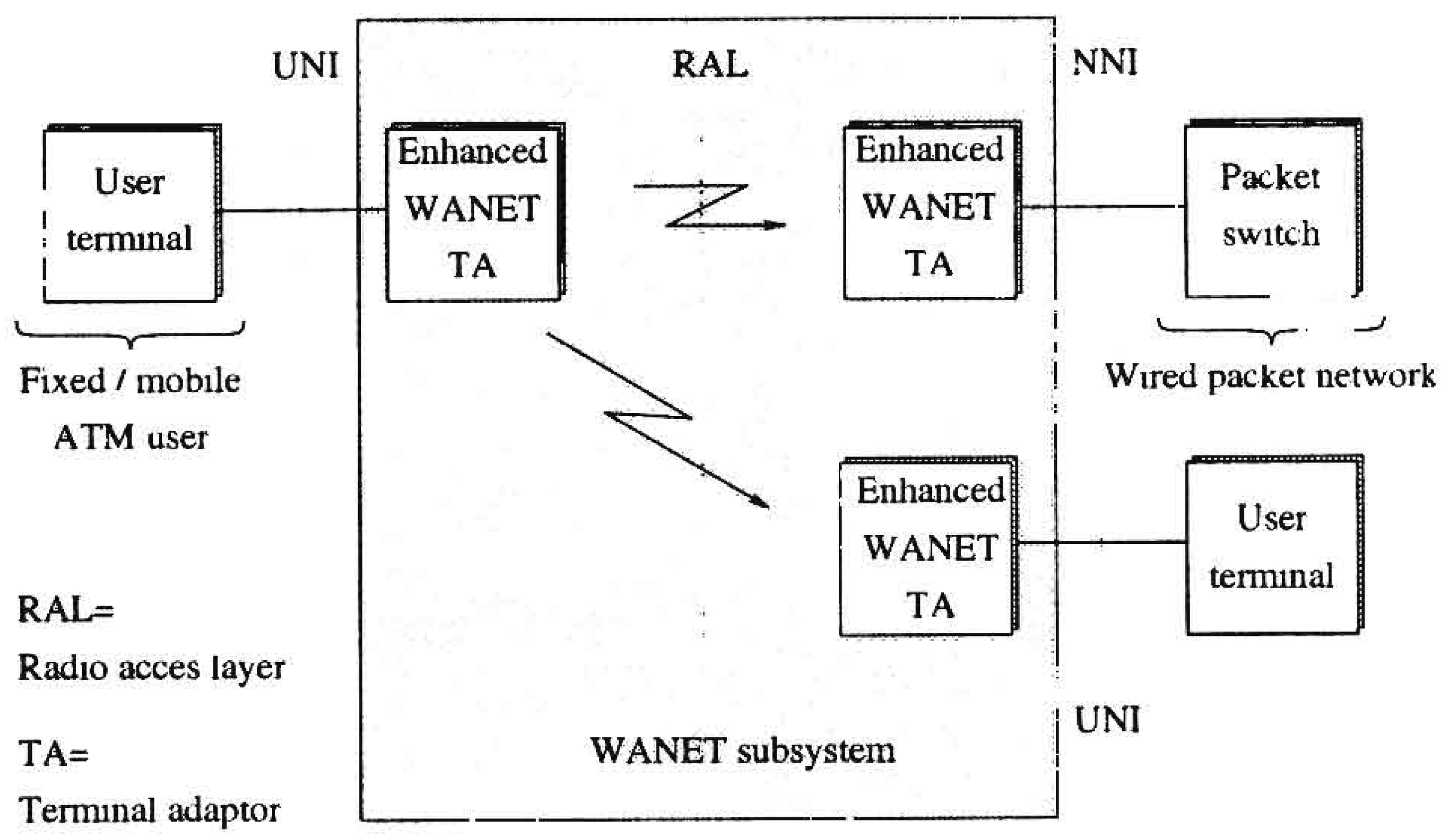

Figure 2: WANET reference model. The interfaces UNI/NNI apply if packets are ATM cells

the Radio Physical Layer (RPL), Media Access Control (MAC) and Logical Link Control (LLC) Layers. Since no VCCs are established for connectionless services, no capacity is reserved and no QoS can be guaranteed by the network for those services.

3.1 WANET Protocol Reference Model

The protocol reference model of the WANET is depicted in Figure 3.

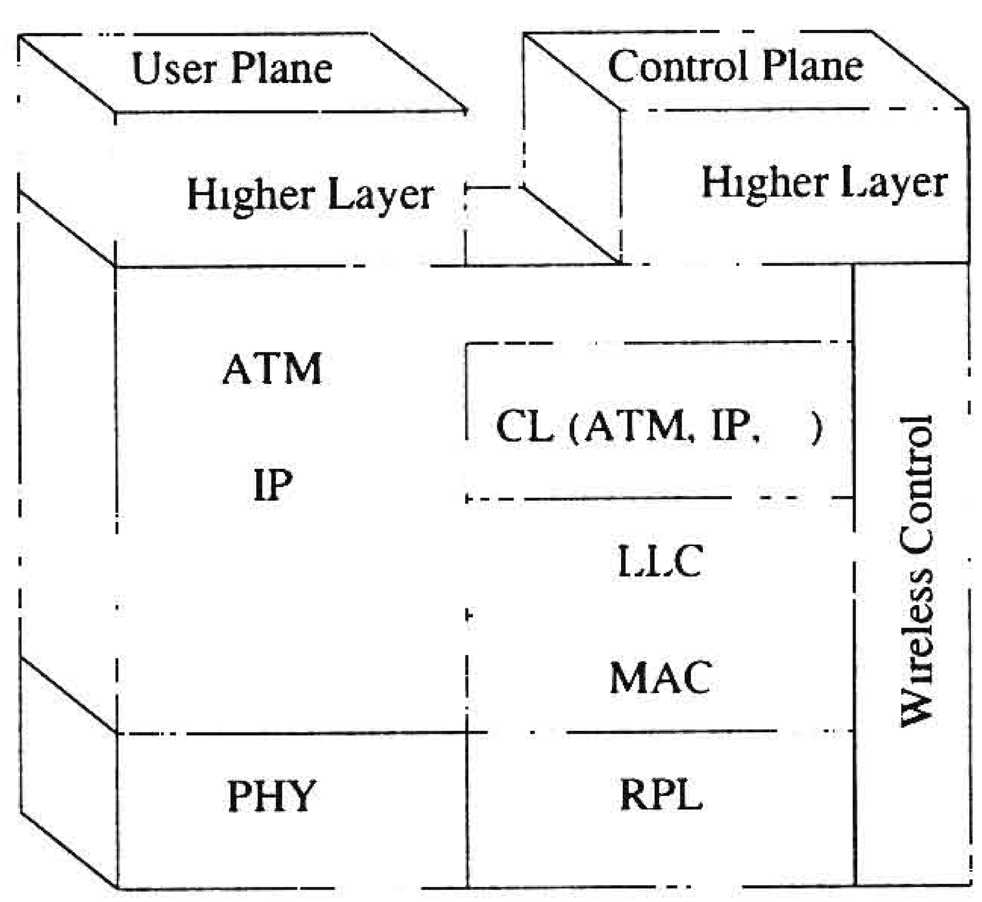

Figure 3: Protocol reference model of the enhanced WANET terminal adaptor

A convergence layer (CL) allows to sit ATM, IP, and IEEE R1394 based systems on top of the air-interface protocols as known from ETSI/BRAN [7]. Therefore, the protocols of the air-interface can be used to support any of the standards mentioned. To support QoS, the LLC layer makes use of information of higher layers, e.g., the service type that is transmitted in the ATM header is used to schedule the ATM cells based on priorities. The respective information is transmitted by the CL to the LLC. The CL performs the segmentation and reassembly of long IP packets to fit the LLC service data units (SDUs) to a length of the payload of one ATM cell. To shorten addresses the ATM header is translated in an abbreviated local VCC identifier (VCC-Id) that is unique in the ad hoc network and has a length of 14 bit. The MAC layer provides transmit capacity to the LLC and supports prioritized random access to acquire new/further transmit capacity.

To guarantee QoS, management of transmit capacity becomes necessary and a wireless connection admission control (CAC) is performed in the wireless control function for that purpose.

3.2 Frame Structure

The frequency band is divided into FDM channels with a width of, e.g., 20 MHz and for each frequency channel time division multiplexing (TDM) channels based on periodic time slots are introduced.
A time slot carries a burst containing fields for settling time for automatic gain control (AGC), synchronization, phase reference, error control (EC) and user data, and has some spare space called guard period [5]. The example TDMA frame comprises 16 slots each having a duration of 23.2 μs for a net data rate of 20 Mbit/s and 448 bit carried in a slot. Each slot provides transmit capacity to the MAC represented by a traffic channel (TCH). Forward error correction is performed by a (76,56)-Reed-Solomon code. To combat large delay spreads and avoid inter-symbol interference, OFDM with 52 sub-carriers (64-FFT) is proposed as transmission scheme. Access with contention is performed on the access channel (ACH). This channel is based on a slot structure that comprises a contention phase of 320 bit and signalling burst of 112 bit, and is described in more detail in section 4.2.

4 THE AIR INTERFACE CONTROL PROTOCOLS

4.1 Logical Channels

Exclusive transmit capacity on the MAC layer for point-to-point communications as long as needed is defined by means of traffic channels (TCH), formed from periodic slots. A TCH x/y is using a number x of slots per frame, where y is the repetition period of these slots counted in frames. E.g., TCH 1/3 defines a physical channel capacity according to 1 slot/frame every third frame, whilst a TCH 3/1 uses three slots every frame, see Figure 4.
For the results in this paper $x \in (1..16)$ and $y = 1$ has been used. Any number of TCHs can be grouped to realize a so-called real channel connection (RCC).
An RCC is a layer 2 logical channel based on one or more TCHs. Its range of validity is for one hop only. The establishment of an RCC requires that a virtual

[5]The guard period is related to the signal propagation delay

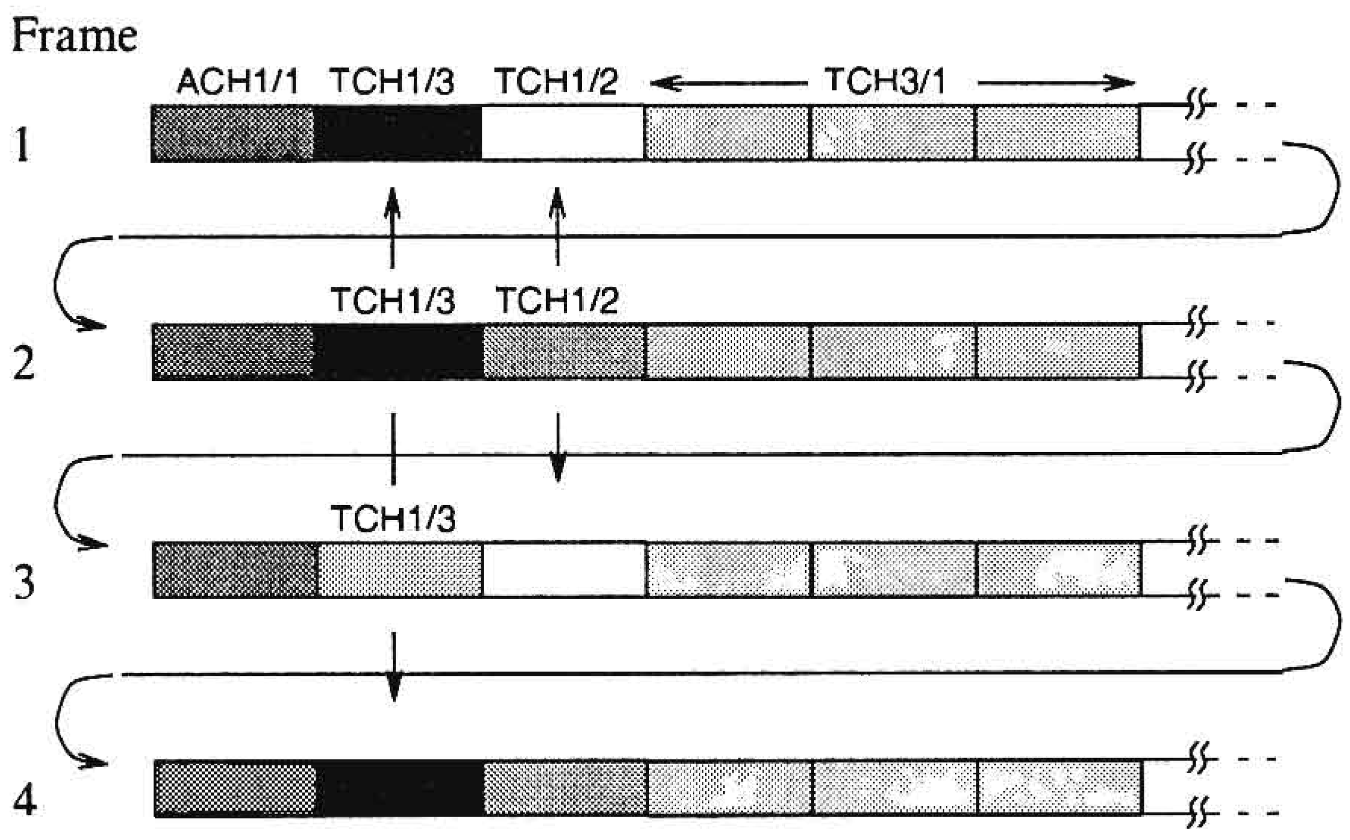

Figure 4: Logical channel structure

channel connection (VCC) (as layer 3 end-to-end connection) has been established before. Otherwise no QoS can be guaranteed and the system would be able to serve IP packets only. A VCC might consist of a sequence of RCCs, each based on a different setting x/y of the related TCHs, e.g. TCH 1/1 for the first hop and TCH 2/2 for the second hop according to the available slots per hop. Different from a VCC an RCC reserves continuously physical transmit capacity during its (short) life time.

TCHs are used in a time-division duplexing (TDD) mode of operation and the number of slots used forward and backward can be defined during establishment. Access channels (ACCHs) are provided to nodes separately in the TDMA-frame to acquire TCHs under the control of a multiple access protocol. An ACCH is realized by an ACH.

The periodic time slots are supervised by the node's management system by periodically measuring their signal strengths and updating a local channel occupancy list (LCO-list) of usable channels. An Organisation Channel (OCH) is used to exchange system connectivity information, parameters of the nodes and network management system and radio resource related information. A TCH x/y is used to realize an OCH throughout the network.

4.2 Reservation of TCHs

To establish an RCC between two nodes an access (ACC) protocol data unit (PDU) is transmitted via the ACH. The PDU contains an ID to identify the type of PDU, e.g. access control or network management, and the addresses of the transmitting and receiving nodes of the one-hop connection. An abbreviated unique VCC identifier refers to a VCC that has been previously established (if the network does support QoS guarantees), and a channel list contains the proposed channels that have been measured to be silent and can be used by the responding node to acknowledge the requested RCC. Further, the PDU comprises signalling information of higher layer protocols, e.g., the QoS that informs the MAC layer about the throughput and delay requirements for the requested RCC.

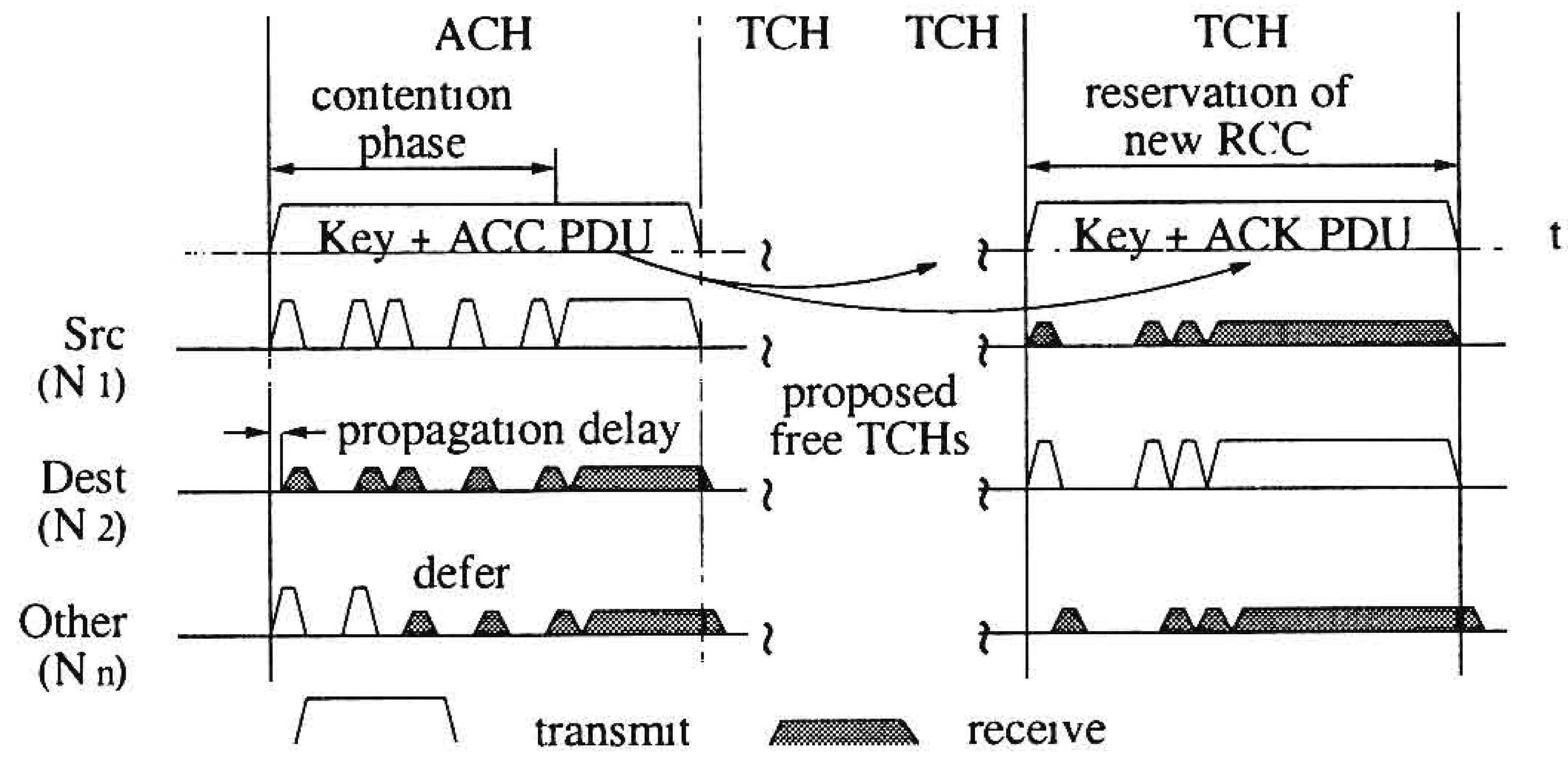

Figure 5: Access mechanism on ACH

The ACC PDU is preceded by a key, a code representing priority numbers. In Figure 5 the key has 40 bit per code symbol and 8 binary symbols per key. The symbol size is chosen to cope with the propagation delay of up to 300 ns. A 'one' symbol is generated by transmitting an energy burst during the equivalence of 40 bit duration whereby the 'zero' symbol carries no energy. With the example key 2^8 sets of energy-burst-and-pause combinations, called keys can be distinguished. The lowest priority is represented by all zeros' and the highest priority of 255 is 'all ones' symbols. A node intending to transmit an ACC PDU uses its own key and listens during its symbol transmit pauses. If another node is heard transmitting, the node defers from transmitting its ACC PDU in the current slot. This access protocol, CSMA/CA[6] is known from the ETSI/HIPERLAN/1 access protocol EY-NPMA [6]. The key length is a design parameter. In the example illustrated in Figure 5 node N_1 uses a key equals "10110101" and another node N_n uses the key "1010xxxx" and therefore defers from transmitting an ACC PDU. The "xxxx" denote any combination of energy bursts and listen periods.

A node, in the example N_1, that was not forced by keys of other nodes to defer sends its ACC PDU to the destination (Dest) N_2, and all other nodes in the transmit range with radius R_{tr} of node N_1 mark the proposed TCHs contained in that message as reserved for a time duration T_{res}.

The destination node, say N_2, if reached selects one out of the proposed channels (if more than one channel is proposed in the ACC PDU) according to a minimum required RSSI margin value out of its LCO-list and responds to the calling node in the respective TCH with an acknowledge PDU (ACK PDU) in the same frame. By this procedure, it is guaranteed that N_2 will reach N_1 safely and vice versa with a high probability. Both PDUs are recognized by the nodes within the detection

[6]Carrier-Sense Multiple Access / Collision Avoidance

range of N_1 and N_2 and all nodes in the receive range of N_1 and N_2 are aware of the TCH being in use as soon as node N_1 is transmitting on the respective channel.
The key contained in the ACK PDU of node N_2 is able to eliminate the rare event that a hidden station (with respect to the transmission of the ACC PDU of N_1 to N_2) has proposed the same channel in its ACC PDU to another node that will content for the same free TCH.
It might be that a node does not receive the answer of S_2 to S_1 and consequently will mark all the channels proposed by S_1 as free after T_{res} has expired. This does not severely harm the functioning of the network since these node soon will measure the allocated TCH in use in a TDD mode of operation.
The next hop, say from S_2 to S_3, is established in the same way. During the establishment of the next RCC on a route along a VCC, the capacity of a previous hop might be increased on demand by signalling the respective demand inband via the existing RCC.

4.3 Data Transfer

After an RCC has been established, the data transfer is started. The packets are transmitted transparently as payload of the data PDU and are acknowledged on the backward channel.
The number of time slots allocated to an RCC can be dynamically changed according to the actual needs of the communicating nodes by transmitting a signalling PDU instead of a data PDU. By this, changes of the capacity of a one-hop link can be performed in a very short time. One possible mode of operation is to keep continuously at least a TCH 1/y for an RCC and dynamically increase/reduce the capacity by opening/releasing parallel TCHs.

4.4 Connection Release of RCCs

An RCC is released when no more packet between the nodes involved in an one-hop connection is available and a pre-defined time-out since the arrival of the last packet is elapsed.
Packet based communication can be described by the packet train model [10]. After an inactive phase of the source, a train of data PDUs is generated with the inter-car gap smaller than a specified maximum, referred to as the maximum allowed inter-car gap (MAIG). The inter-car gap is defined as the time between the end of a data PDU and the time of arrival of the following one. Consecutive trains are separated by inter-train gaps. We propose to define a train so as to contain the MAIG as a parameter, controlled by the management system dependent on the current load of the network.
The inter-train gap is a second parameter to control the life-time of an RCC and to define the MAIG. It is measured by the network management system. The MAIG might be defined service class specific.
An RCC is released either explicitly through a connect release message from one of the nodes involved in a hop, or by a decentralized decision from the other nodes observing that the respective MAIG has been exceeded. Then the respective slots are marked as free in their LCO-list.
To adapt the reservation of capacity to the varying load the number of ACHs is dynamically adjusted depending on the train length observed by the management system and is communicated via the OCH. With increasing train length the access intensity decreases and thus the number of ACHs can be decreased. A node is allowed to multiplex traffic of different applications and related VCCs to a given RCC to increase the train length.

4.5 Pre-emptive Priorities for Real-Time Services

A wireless LAN serving as extension of a wired ATM network needs be able to support both continuous and real-time variable bit rate (CBR, rt-VBR) services, which have more stringent delay requirements than other services (VBR, ABR, UBR). Therefore, prioritized channel access and interruption of low priority services are used.

4.5.1 Prioritized Access

To guarantee the QoS according to the traffic contract sets of keys for access PDUs with different priorities are provided and decentrally assigned. The key will avoid collisions across service classes. For real-time oriented services a set with a high priority is assigned allowing the quick re-establishment of an RCC when the next packet train arrives. This key will define an energy signal at the beginning of the contention phase. ABR and UBR service classes are assigned low priorities, that means they will start listening on the channel before they are allowed to transmit an energy signal to gain access on the ACH. If a node has been forced to defer during an access trial the key priority might be increased for the next attempt to improve the probability of success.

4.5.2 Pre-emption of RCCs

A node N_1 that needs to re-establish an RCC to another node N_2 and that is unable to name silent TCHs may interrupt an RCC supporting a low priority service. If no low priority RCC is available to be interrupted, N_1 transmits an access PDU (with an empty proposal of free channels) to N_2. In a responding access PDU N_2 will transmit on the ACH proposed TCHs that have been interrupted for a short while. N_1 will select the proposed TCHs with respect to their interference level and responds accordingly. N_2 will continue service on these channels not being chosen by N_1. Trains with a higher (service class related) priority thus will be able to interrupt lower priority services on the hop considered.

4.5.3 Forced Release

Another measure to support real-time oriented traffic it to reserve at least one channel for high priority services. When this channel will be accessed to support the respective service class, a node that operates a connection with lower priority will implicitly release the respective reserved TCHs to guarantee that a node with high priority service will always find a free channel [16].
The mechanism described so far requires continuous supervision of channels at all the active nodes that are operating a channel or intending to open one in the near future. Its benefit is that a nearly perfect decentrally organized channel allocation is possible in a hidden station environment, assigning those channels to be used on a hop that are the most silent ones seen from the communicating nodes.

4.5.4 Logical Link Control (LLC)

The LLC layer applies an ARQ protocol on a per hop basis. The data PDU contains one byte for piggybacked acknowledgements and another byte for a cell sequence counter. If no data is available to be transmitted on the reverse channel that can carry the ARQ information a signalling packet is transmitted instead on the RCC. Advanced scheduling strategies based on priorities derived from due-dates of data PDUs, an expiry date, and the number of hops travelled might be used to differentiate between the data PDUs transmitted on the same RCC. Data PDUs may be dropped before transmission if their due dates cannot be met. Especially for long IP packets, that are segmented at the convergence layer (CL), all packets that belong to one IP packet are discarded if one packet is dropped, since the whole IP packet then is useless. The CL therefore has to indicate the packet begin and packet end for a long packet that is segmented.
Besides the forward error correction on the physical layer the PDU is protected through an error detection checksum.

5 POWER SAVING MODE

Power saving is important in wireless LAN with movable or mobile nodes due to their limited battery capacity. The proposed scheme is able to support some percentage of mobile nodes unable to continuously follow what is going on and possibly being not willing to relay traffic of other nodes. The latter has no impact on the functioning of the network but only on the meshing density, since the connectivity of nodes is reduced then. nodes that are not willing to transmit may switch to a sleeping mode To enable nodes to be addressed and reached even when sleeping, sometimes they must select a nearby (fixed) node and inform it when during their next planning horizon they will power on and be ready to receive.

6 CONNECTION ADMISSION CONTROL

To be able to support real-time services with an appropriate QoS, these services are assumed to open a virtual channels connection before transmitting user data. A decentralized connection admission control (CAC) algorithm has been developed that is able to guarantee the QoS aimed at [11]. This CAC algorithm calculates at each node the available transmit capacity and a new connection is accepted, if the required capacity for this connection does not exceed the available capacity. A new virtual end-to-end connection will be accepted if on every link this procedure is successful.
Non real-time services need not to apply for admission but will be interrupted whenever real-time services need the radio capacity occupied by them. Of cause it appears practical also to apply some admission rules for non real-time services to guarantee them at least some minimum average throughput.

7 PERFORMANCE RESULTS

The protocols described above have been analyzed by means of event-driven stochastic simulation. Different radio connectivities of nodes have been considered and the impact on the performance of end-to-end connections have been investigated.
The connectivity of a radio network is defined by the mean number of nodes reached in one radio hop (neighbour), normalized by the number of all the other nodes N,

$$c = \frac{1}{N(N-1)} \sum_{i=1}^{N} n_i, \tag{1}$$

where n_i is the number of neighbours to node i. For a fully meshed network the connectivity is 1.
Networks with 20 nodes distributed uniformly in an area with a connectivity of 1, 0.77, 0.57 and 0.5 have been studied. Nodes once for ever randomly select their final destination node and service class. No signal fading is taken into account; the packet error ratio (for all PDUs) is set to 1 % instead.

7.1 Traffic Source Models

The nodes have identical source traffic behaviour and generate symmetric traffic. Two traffic sources are modeled by a Poisson stream of packets with constant length either of 53 byte (source 1) or 1590 byte (source 2) corresponding to a bulk arrival of 30 ATM cells. A third class (source 3) is modeled by an autoregressive process of first order with constant packet interarrival time of 33 ms and used to model VBR traffic sources with mean packet sizes between 206 and 1856 byte.
For the following simulation study, the maximum allowed inter-car gap is assumed to be two frames.

7.2 Impact of the Connectivity on Throughput and Mean Delay

Figure 6 shows the payload throughput over the traffic load for networks with connectivity 1.0, 0.77, 0.57 and 0.5 for source 2.

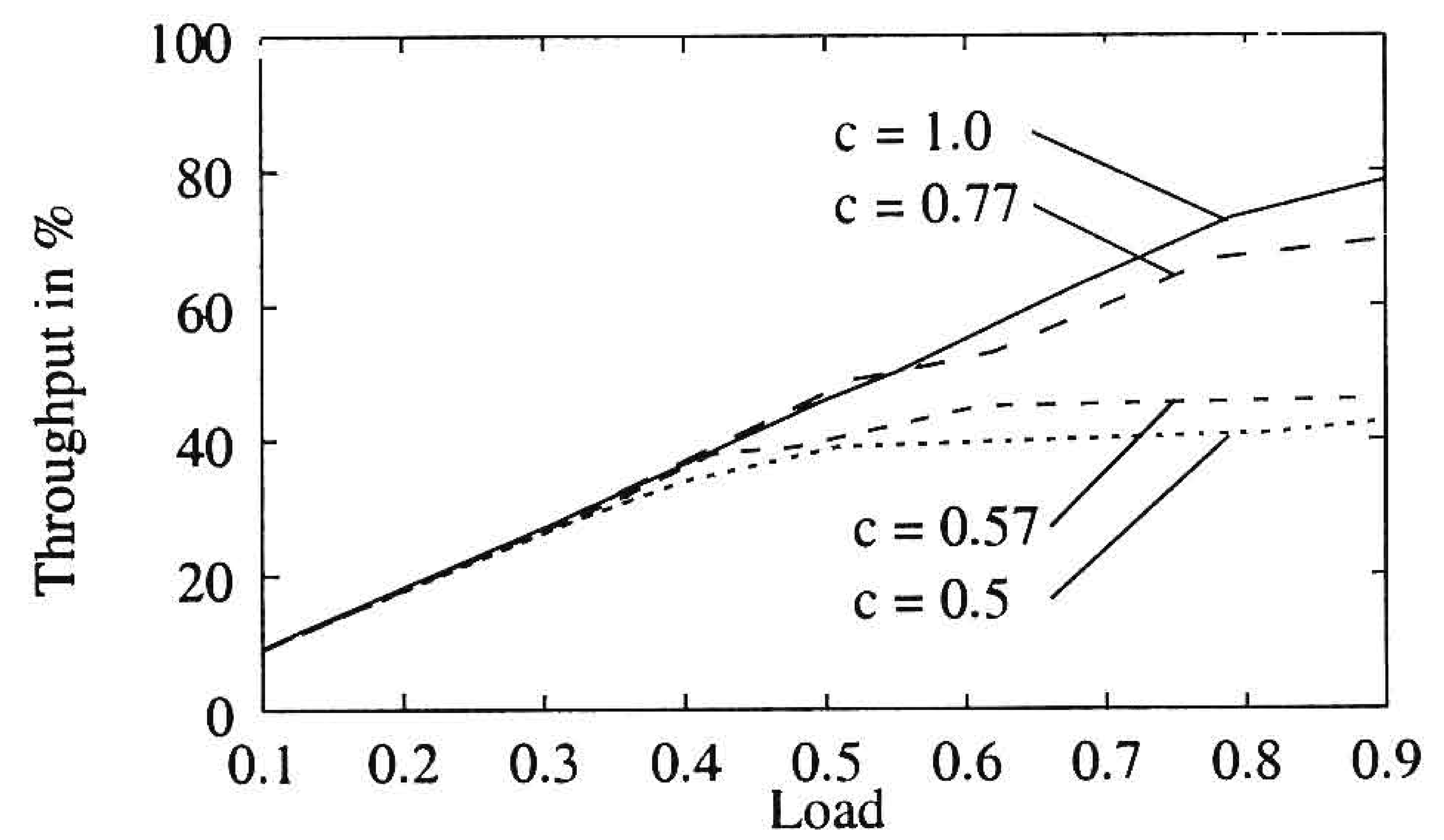

Figure 6: Throughput vs. offered traffic for source 2

The offered traffic load results from the payload (ATM cells) only and is related to the available transmission capacity of 20 Mbit/s. Due to protocol overhead at the air interface the payload throughput is more limited dependent on the connectivity. With a connectivity of 0.5 the network is saturated for an offered traffic of 50% of the transmission rate. A mean number of 2 hops per end-to-end connection for this connectivity has been observed so that the load is approx. twice the offered traffic.
Because of the long packets (source 2) and the large sojourn times, trains typically consist of a continuous stream of data PDUs and the one-hop connection is released after each packet. Throughput linearly increases with load until saturation is reached. For the connectivities of 0.77 and 0.57 the mean numbers of hops per end-to-end connection are approx. 1.3 and 1.5, respectively.
The end-to-end mean delay of ATM cells of source 2 packets shown in Figure 7 is nearly constant until the network approaches saturation. The capacity of TCHs for each RCC have been increased dynamically with load in this simulation experiment to keep delays small. Thresholds for the number of cells in the queue are used to determine when a new TCH has to be allocated for an RCC and when a TCH can be released again. Under high load the delay increases substantially as the

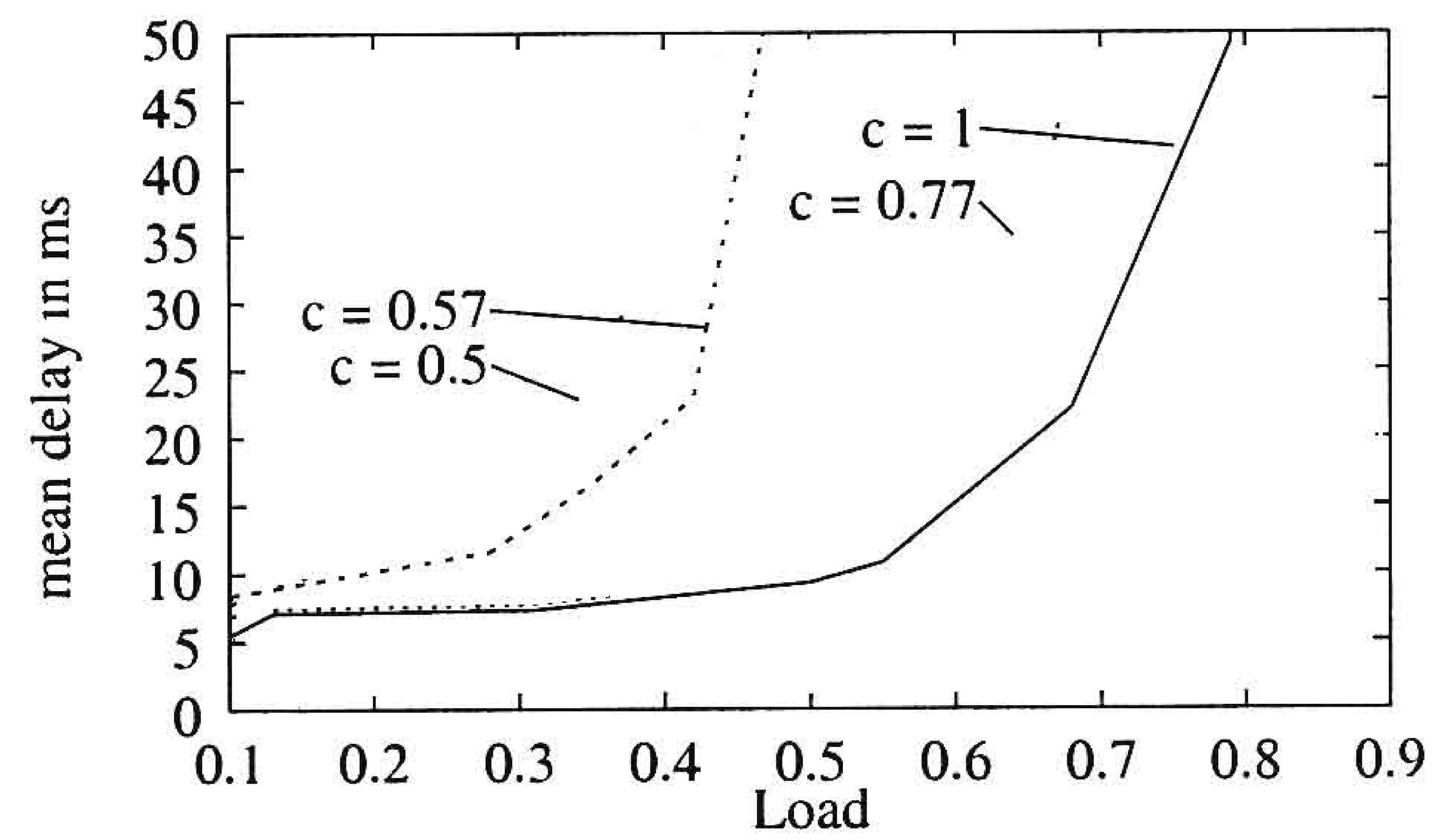

Figure 7: End-to-end delay vs. offered traffic for source 2

network is then running into high load conditions and queueing in buffers dominating.

7.3 Impact of Traffic Sources on the Performance

It has been found, that the throughput is more or less independent of the traffic source characteristics assumed. The respective cumulative distribution function (CDF) of the delay for different traffic loads are depicted in Figure 8.

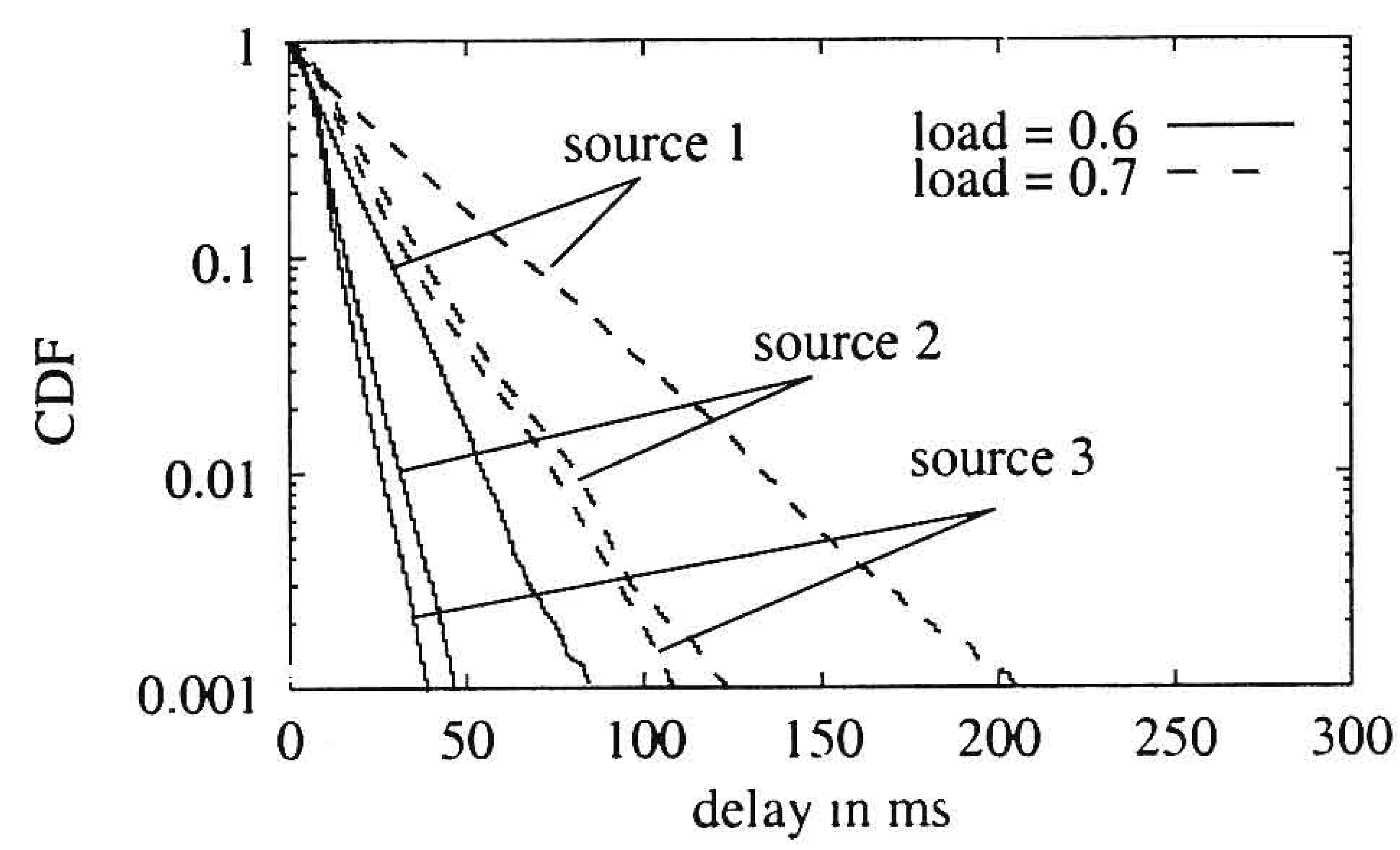

Figure 8: CDF of delay for source 1, 2 and 3, c = 1.0

Highest delay values result from the Poisson sources (source 1 and 2). The correlated packet arrivals of the video source 3 can be well served by RCCs so that under 60% load no ATM cell expires a delay exceeding 45 ms. A W-ATM LAN will typically not be loaded by rt-VBR services to such a high percentage of its capacity. Since non-real-time VBR and ABR/UBR service classes will be interrupted in favour of rt-VBR if necessary, rt-VBR sources will see a system with a small load only.

8 CONCLUSION

A self-organized wireless LAN supporting ad hoc and multihop operation with guaranteed QoS has been presented and the performance analyzed. The air-interface of the WANET is designed to efficiently support wireless ATM and thus is suited for multimedia scenarios. To support ATM traffic with given QoS constraints connection admission control for wireless systems has been introduced. Using real channel connections based on TDMA frames contention free data transmission can be realized. Prioritization of real-time oriented traffic is realized by access priorities and pre-emption of low priority services. Even when the network is highly loaded and hidden stations are present a high throughput and a small delay can be achieved. The protocols are unable to reduce the delay below some fixed value (say about 1 ms at 20 Mbit/s per hop) needed to establish an RCC connection. Most important features are the fast RCC setup, decentral RCC release, the concept of packet trains, pre-emption of low priority services and the ability to guarantee QoS in a hidden station environment.

References

[1] F. Bauchot, et al. *MASCARA, a MAC Protocol for Wireless ATM.* In *ACTS Mobile Communications Summit*, pp. 647 - 651, Granada, Spain, November 1996.

[2] L. Dellaverson. *SAMA Multiple Access - Further Inputs.* Contribution to ETSI EP BRAN, October 1997. Motorola Radio Research Lab.

[3] J. Deng, Z. Haas. *Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks.* In *IEEE International Conference on Universal Personal Communication (ICUPC)*, pp. 973-977, Florence, Italy, October 1998.

[4] Y. Du et al. *System architecture of a home wireless ATM network.* In *IEEE ICUPC*, pp. 477-481, Sep 1996.

[5] ETSI. *Radio Equipment and Systems, Digital European Cordless Telecommunications, Draft prETS 300 175.* ETSI, August 1991.

[6] ETSI. *Radio Equipment and Systems (RES); High PErformance Radio Local Networks (HIPERLANs) Type 1 Functional specification.* Draft prETS 300 652, ETSI, Sophia Antipolis, France, 1996.

[7] ETSI-BRAN. *High Performance Radio Access Local Area Network - Type 2 (System Overview).* Draft DTR/BRAN-00230002, ETSI, Sophia Antipolis, France, February 1999.

[8] PHS MoU Group. *PHS MoU Group, Technical Specifications List.* available via http://www.phsmou or.jp/tech1.html, 1998.

[9] P. Humblet, S. Hethuin, Hrsg. *A Multiaccess Protocol for High-Speed WLAN*, Vol. 1, p.257-261 of *VTC Proc.*, 1996.

[10] R. Jain, S.A. Routhier. *Packet Trains - Measurments and a New Model for Computer Network Traffic.* IEEE Journal on Selected Areas in Communications, Vol. SAC-4, No. 6, pp. 986-995, September 1986.

[11] M. Lott, B. Walke. *Performance analysis of a Wireless Ad hoc Network with QoS Support.* In *Symposium on Performance Evaluation and Telecommunication Systems (SPECTS'99)*, Chicago, Illinois, July 1999.

[12] LAN/MAN Standard Committee of the IEEE Computer Society. *IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications* . Standard, IEEE, June 1997.

[13] LAN/MAN Standard Committee of the IEEE Computer Society. *Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: High Speed Physical Layer in the 5 GHz band.* Draft Supplement to IEEE 802.11a/D2.0, IEEE Standards Department, 1998.

[14] D. Petras, A. Krämling, A. Hettich. *MAC protocol for Wireless ATM: contention free versus contention based transmission of reservation requests.* In *PIMRC'96*, pp. 903-907, Taipei, Taiwan, October 1996.

[15] B. Walke, S. Böhmer, M. Lott. *Protocols for a Wireless-ATM Multihop Network.* In *International Zurich Seminar*, pp. 75-82, February 1998.

[16] B. Xu, B. Walke. *Protocols and Algorithms Supporting QoS in an Ad-hoc Wireless ATM Multihop Network.* In *Proc. of EPMCC'99*, pp. 79-84, Paris, France, March 1999.