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Distribution and Availability on Back Cover

A Wireless Ad hoc Multihop Broadband Network with Quality of Service Support

Matthias Lott, Bernhard Walke
Communication Networks, Aachen University of Technology, D-52074 Aachen, Germany
E-Mail: {lott,walke}@comnets.rwth-aachen.de

Abstract In this paper a wireless ad hoc multihop network is described. The decentrally organized network is able to guarantee the bandwidth contracted to a connection in a hidden station environment by means of contention-free data transmission on real channel connections (RCCs) that are established and used for the duration when data have to be transmitted, and that are released otherwise. Protocols for the air interface of the proposed network that have been developed to support real-time oriented services with quality of service and that support the prioritized, quick re-establishment of real channel connections are described.

The proposed algorithms efficiently exploits the available frequency spectrum and protects established links in a hidden and exposed station environment. Performance results for the ad hoc network with different connectivities are presented and indicate low delay and high utilization even for multihop operation.

Keywords— ad hoc, multihop, self-organizing network, hidden station, exposed station, dynamic channel allocation, decentral control, quality of service, prioritized access

I. Introduction

AD HOC wireless communication has been of interest for a long time in military tactical communication [1] Besides, mobile ad hoc computing is becoming more attention in the commercial communication, too [2], [3]. This has been started with the standardisation of 802 11 [4], and HIPERLAN[1]/1 [5], [6], that rely on the MAC[2] protocols carrier sense multiple access (CSMA) with collision avoidance (CA) and EY-NPMA[3], respectively, to assign transmission capacity to competing stations within a radio cell Improvements with respect to collision probability have been proposed in [7]

Current proposals for MAC protocols for wireless ATM[4] systems at 5 2 GHz with data rates up to 54 Mbit/s rely on dynamic slot assignment (DSA) TDMA/TDD[5] MAC schemes and the concept of nodes that centrally control the transmission of stations [8], [9], [10], [11] Though, at the moment the standardisation of HIPERLAN/2 focuses on systems with central control represented by an access point (AP) to a fixed network and one-hop communication of wireless stations to the central node, the need for ad hoc systems, that operate in environments without an infrastructure, will become more important. One typical future application is the connection of fixed, movable or mobile stations to a fixed network access point across a so-called ad hoc network, in which stations themselves identify their current radio connectivity from their current location and the other active stations [12]. They calculate the route across intermediate (relay) stations over multiple one-hop connections (multihop connection) to the final destination station [13]. This application includes the replacement of an indoor local area network (LAN) by a wireless network. Other applications are in-house networks that connect portable electronic devices with plug-and-play features [14], mobile computing in conference sized ad hoc mobile environments, and radio LAN outdoors, e.g. for rescue missions

Different from the protocols mentioned above the proposed network relies on self-organized stations with decentral control able to route forward (relay) packets received according to virtual channel connections (VCC) established beforehand, and on dynamic channel allocation (DCA) and the concept of real channel connections (RCCs) [15]. This approach combines the advantages of decentrally controlled channel access with reservation based collision-free transmission of packets in containers of a framed TDMA system in a hidden station environment.

Next to the general problem of hidden and exposed stations (sec II), protocols for the air-interface developed for ad hoc networks are presented in section III. To guarantee quality of service the best as possible in wireless networks, decentral scheduling and connection admission control schemes are proposed in section IV and VI, respectively. Results for the proposed ad hoc network that have been derived by means of stochastic event-driven simulations and that demonstrate the ability to guarantee the QoS aimed at are summarized in section VII.

II Hidden and Exposed Stations

Ad hoc radio networks are characterized by stations that are placed randomly over the area and built a network in a spontaneous manner. Thus, no radio coverage planning can be applied and in many cases not all of the terminals in the ad hoc network have direct radio contact to each other.

A. Hidden station

In the latter case a station S_1 forwarding a packet to some other station S_2 is unable to control the usage of the respective radio medium in the receive range of the station addressed (c f. Fig 1)

A so called hidden station S_3 with a distance to the transmitter, that is larger than the detection range R_{det}, might

[1] High Performance Radio Local Area Networks
[2] Medium Access Control
[3] Elimination Yield-Non-Preemptive medium access
[4] Asynchronous Transfer Mode
[5] Time Division Multiple Access/Time Division Duplexing

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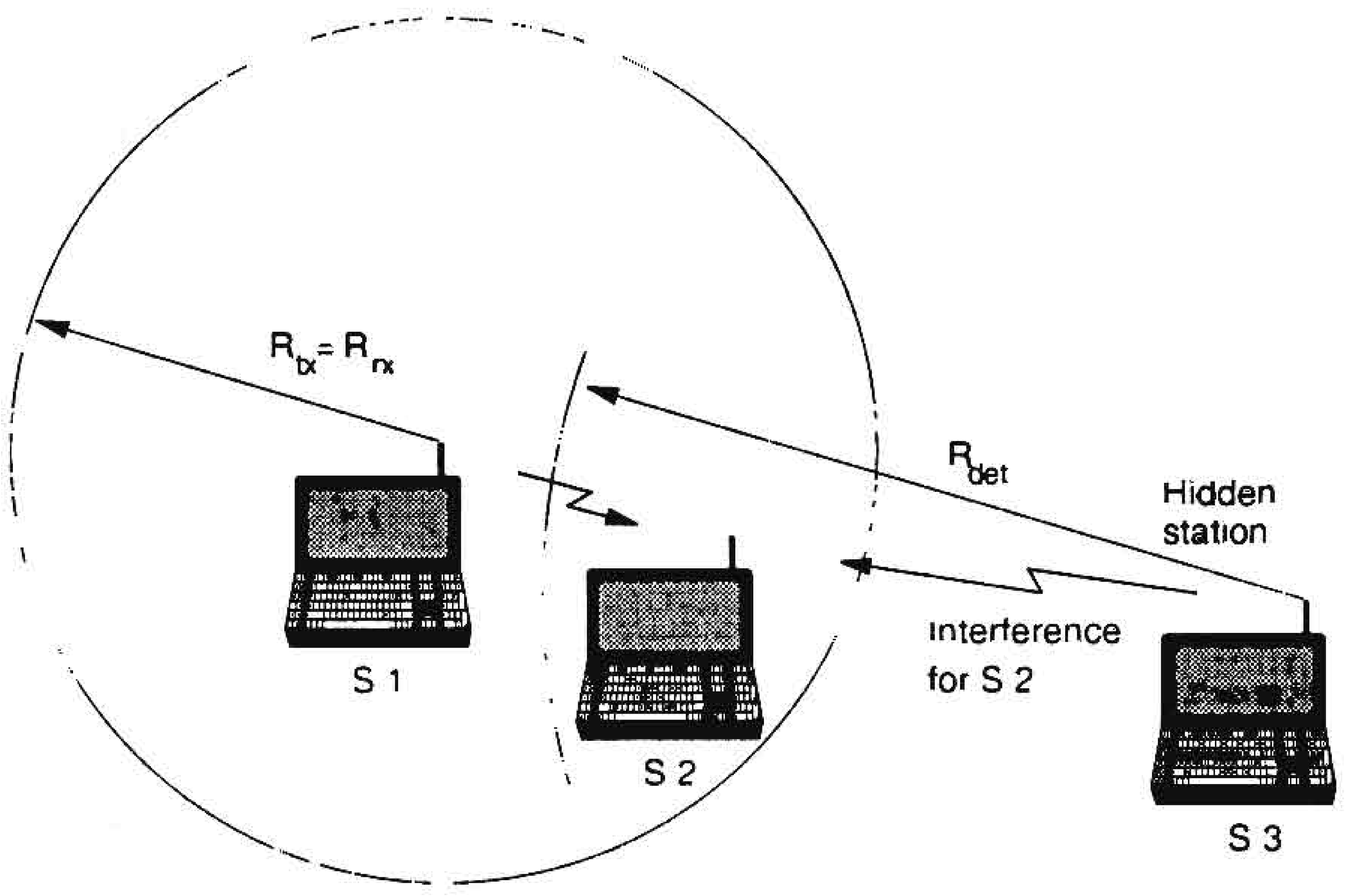

Fig 1 Interferences for non-synchronized systems in a hidden station environment

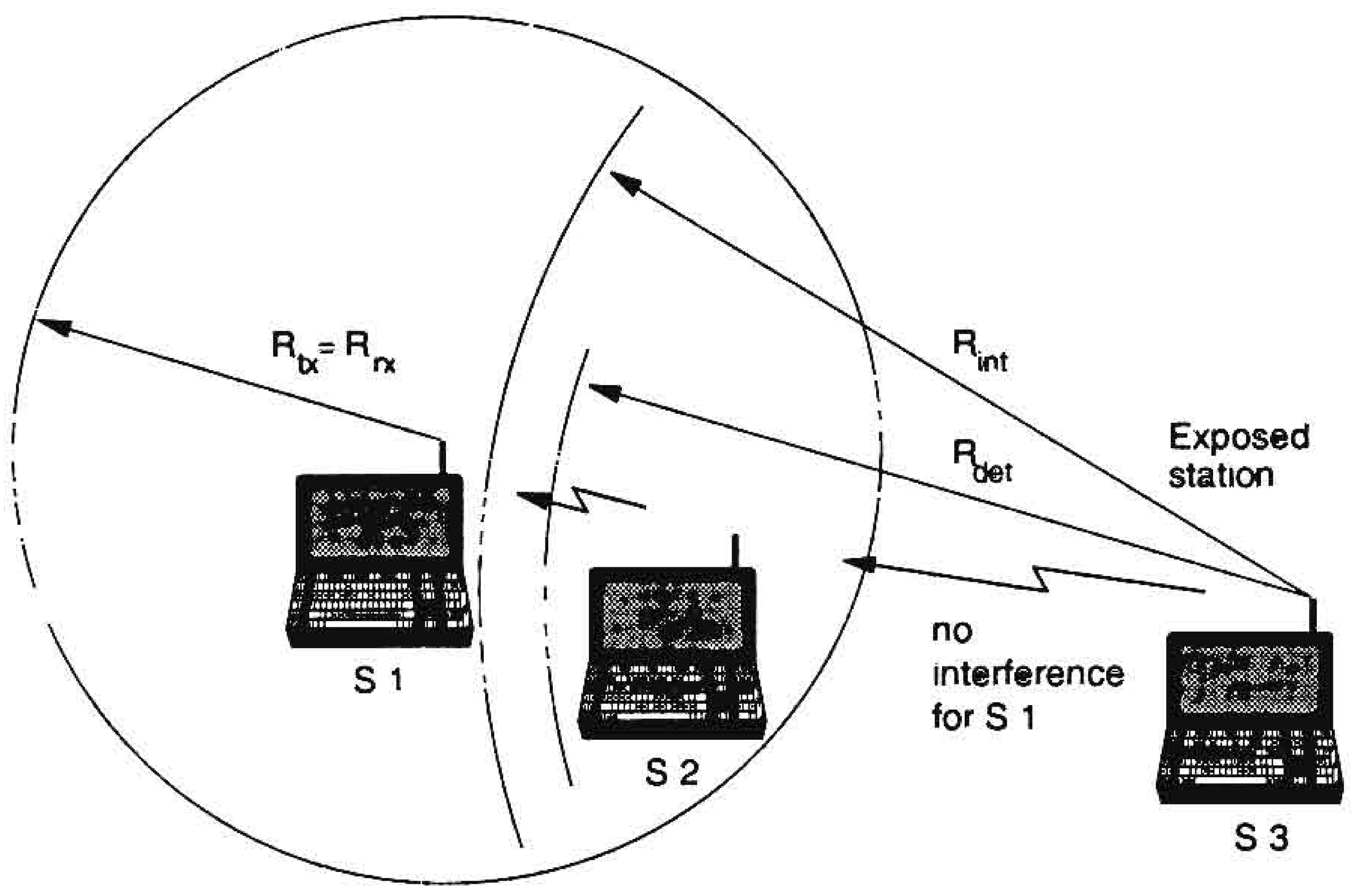

Fig. 2 Exposed station

cause interference at the receiver at the same time since neither the transmitter nor the interferer are aware of the transmission process of the other station

Hidden stations affect the system throughput severely and tend to make a quality of service (QoS) guarantee impossible. The problem always arises when no means are available in a system to extrapolate from the presently observed spectrum occupancy to the future usage, e.g., of a time slot. Real channel connection (RCC) (see also sec. III-C) based systems are potentially better suited to guarantee an agreed transmission capacity in an ad hoc environment than systems based on dynamic slot assignment or random MAC protocols, since they operate with unpredictable random usage of the radio medium in the receive range of any node or station involved An RCC is synchronously used in time-division duplexing (TDD) mode and the position in time of the potential interference energy is therefore known by any station within the detection range of the transmitter and receiver. Hidden stations are aware of the RCC in use and are forced to cooperate. The channel oriented communication has the advantage that an RCC measured by some station to have a too high signal strength will not be used by that station, since with a high probability it will find the channel still occupied in the near future

B Exposed station

Another problem in partially meshed networks that decreases the spectral efficiency are exposed stations, as shown in Fig. 2.

A station is called exposed if it resigns to transmit at some time to not interfere another communication relationship but in fact could communicate without disturbing the respective communication E g., a station S_3 detects a station S_2 transmitting to another station S_1 and defers from transmission to avoid a collision But if the receiver S_2 is located outside the interference range R_{int} of the potential transmitter S_3, a simultaneous transmission of S_3 would cause no collision at station S_1. With the introduction of RCCs the stations will measure the received signal strength (RSSI[6]) of the two stations using an RCC and then are able to decide whether they are exposed stations or not.

[6]Received Signal Strength Indicator

C Multihop operation

The aforementioned problems are typical in ad hoc networks with partial connectivity and where multihop connections have to be established to reach all stations within the network. Therefore, stations require a radio relay function implemented to extend the one-hop connection between two stations that have radio contact by another one-hop connection, and so on, to a multihop connection for an end-to-end relation between two stations without radio contact Typically, only a small amount of hops is recommended to limit the end-to-end packet transmission delay that is a critical parameter for real-time oriented traffic.

In the following protocols for the air-interface are presented that are based on RCCs. They can cope with hidden stations and can make use of exposed stations to most efficiently use the spectrum. Because of independent operation of stations and their partial connectivity, each station has a different view of the interference situation. The proposed protocols are designed for self-organized stations with switching capabilities and use decentrally controlled medium access.

III WANET Protocol Stack

The proposed wireless ad hoc network (WANET) is aimed to be able to support the QoS known from ATM fixed networks.

A. Frame structure

The physical channels result from dividing the given frequency band into FDM channels and from introducing TDM channels based on periodic time slots used in a TDD mode of operation, cf Fig. 3.
A time slot carries a burst containing fields for settling time for automatic gain control (AGC), synchronization, error control (EC) and user data, and has some spare space called guard period to account for the propagation delay. The example TDMA frame comprises 16 slots each having a duration of 23 2 μs for a data rate of 20 Mbit/s and 448 bit

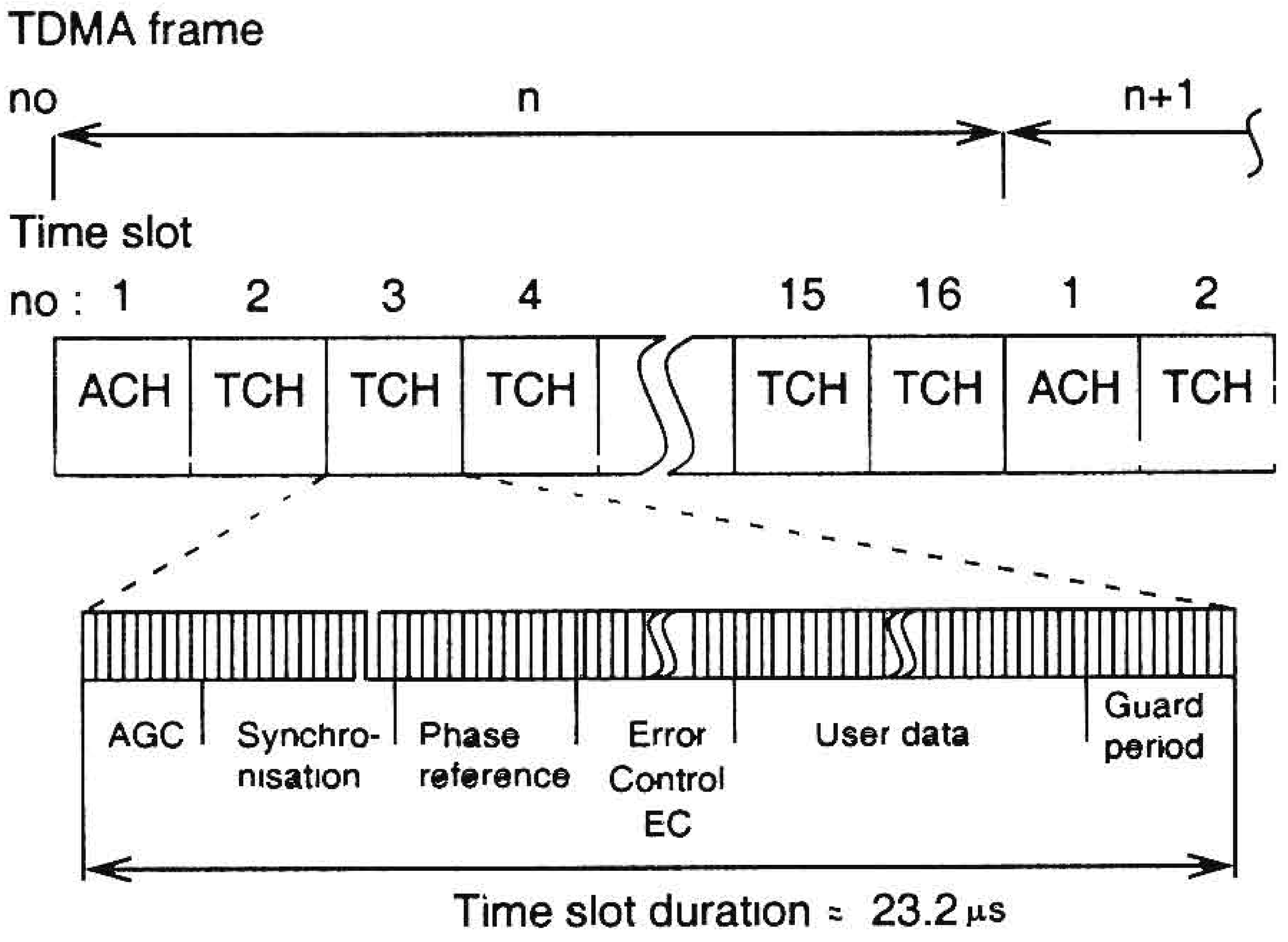

Fig 3 Frame structure (370 μs)

carried in a slot Each burst transmitted in a slot provides transmit capacity to the MAC protocol represented by a traffic channel (TCH). Random access with contention (using a key) is performed on the access channel (ACH). This channel is based on a slot structure that comprises a contention phase of 320 bit duration and signalling burst of 112 bit. The structure of the ACH is described in more detail in the following Section III-C that deals with the reservation of TCHs for one-hop connections.

B Logical channels

Traffic channels (TCH), formed from a number of periodic slots, provide exclusive transmit capacity on the MAC layer for point-to-point communications as long as needed. 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 Fig 4.

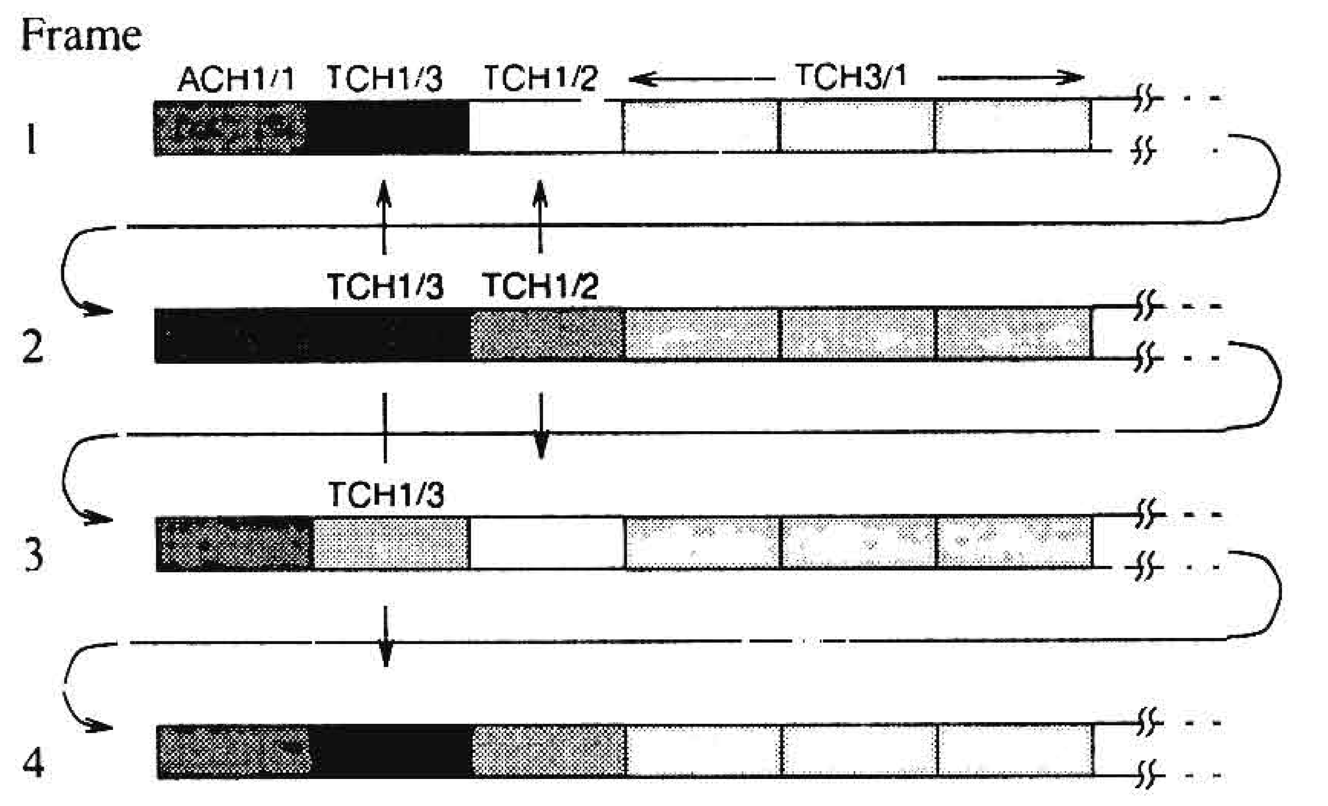

Fig 4 Logical channel structure

By means of defining different slot-to-frame relations sub-multiplexing of the transmit capacity is possible. The smallest traffic channel capacity available is TCH 1/y where y is a design parameter that is chosen according to the traffic characteristic and QoS requirements For the results in this paper $y = 1$ 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 channel connection (VCC) has been established before as a layer 3 end-to-end connection Otherwise no QoS can be guaranteed and the system would be able to serve connectionless data transmission only, e.g. IP packets. 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 continuous physical transmit capacity during its (short) life time

TCHs are used in a time-division duplexing mode of operation and the number of slots used forward and backward can be defined during establishment and dynamically during the data transfer phase (see also Section III-D.2). Access channels (ACHs) are provided separately in the TDMA-frame to allow stations to acquire TCHs under the control of a multiple access protocol.

All periodic time slots are supervised by the station's management system by periodically measuring their signal strengths and updating a local list of usable channels An Organisation Channel (OCH) is used to exchange system connectivity information, parameters of the stations and network management system and radio resource related information A TCH x/y is used to realize an OCH throughout the network. Depending on the number of slots per frame the parameters x and y are chosen to provide the required capacity for the updates.

C. Reservation of transmit capacity for one-hop connections

To establish an RCC between two stations an access (ACC) protocol data unit (PDU) is transmitted via the ACH. The PDU is protected by a frame check sequence (FCS) to detect errors and contains an ID to identify the type of PDU, e.g. access control or network management, cf. Fig. 5, and the addresses of the transmitting and receiving stations 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 guarantee), and a local channel list contains the proposed channels that have been measured to be silent and can be used as TCHs by the responding station 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.

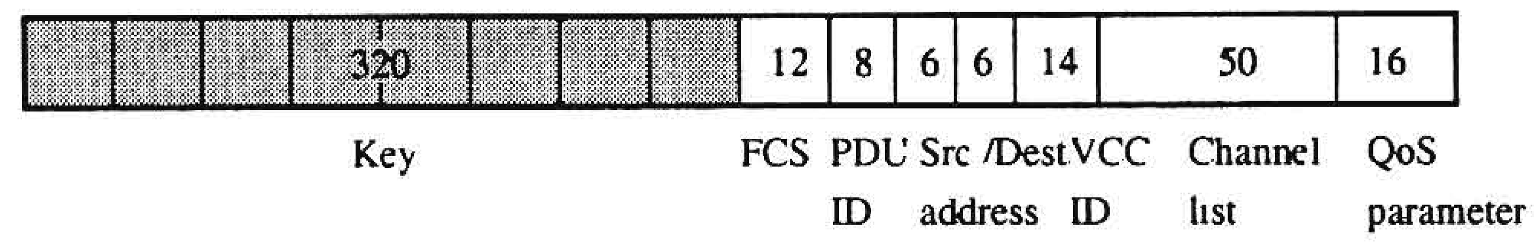

Fig 5 Access PDU

The ACC PDU is preceded by a key, a code representing priority numbers. In Fig 5 the key has 40 bit per code symbol and 8 binary symbols per key. A 'one' symbol is generated by transmitting an energy burst during the equivalence of 40 bit duration whereby the 'zero' symbol carries no energy and defines an equivalent listening duration 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 station intending to transmit an ACC PDU uses its own key and listens during its symbol transmit pauses. If another station is heard transmitting the station defers from transmitting its ACC PDU in the current slot This access protocol, CSMA/CA[7] is known from the ETSI/HIPERLAN/1 access protocol EY-NPMA [5] The key length is a design parameter CSMA/CA serves to reduce the collision probability of an ACC PDU (see also sec. VII)

A station, say S_1, that was not forced by keys of other stations to defer sends its ACC PDU to the destination (Dest) S_2, cf. Fig. 6, and all other stations in the transmit range with radius R_{tx} of station S_1 mark the proposed TCHs contained in that message as reserved for a time duration T_{res}

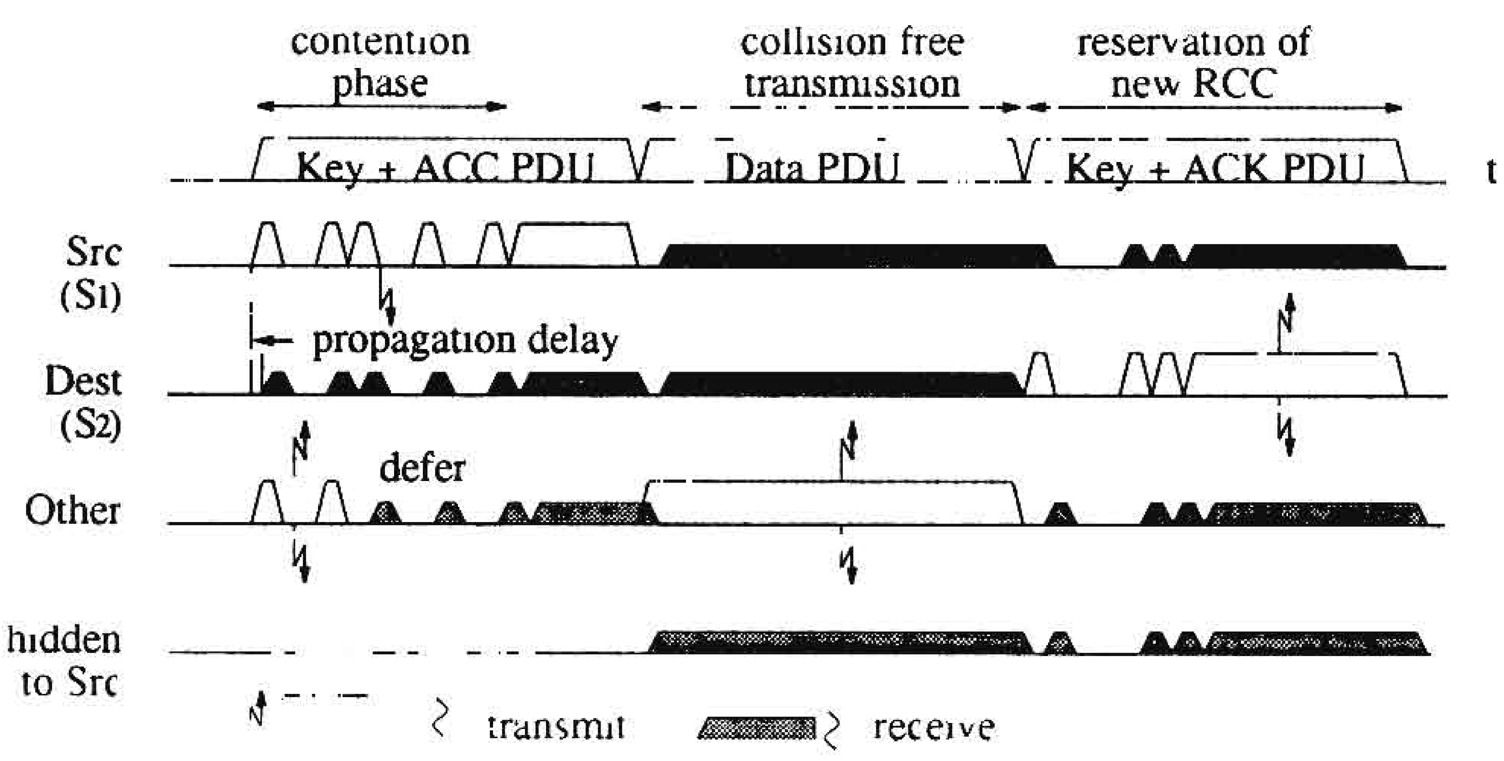

Fig 6 Connection set-up with collision avoidance

The destination station, say S_2, if reached selects one out of the proposed channels according to a minimum required RSSI margin value out of its local channel occupancy list and responds to the calling station in the respective TCH with an acknowledge PDU (ACK PDU) in the same frame, cf. Fig 7 By this procedure, it is guaranteed that S2

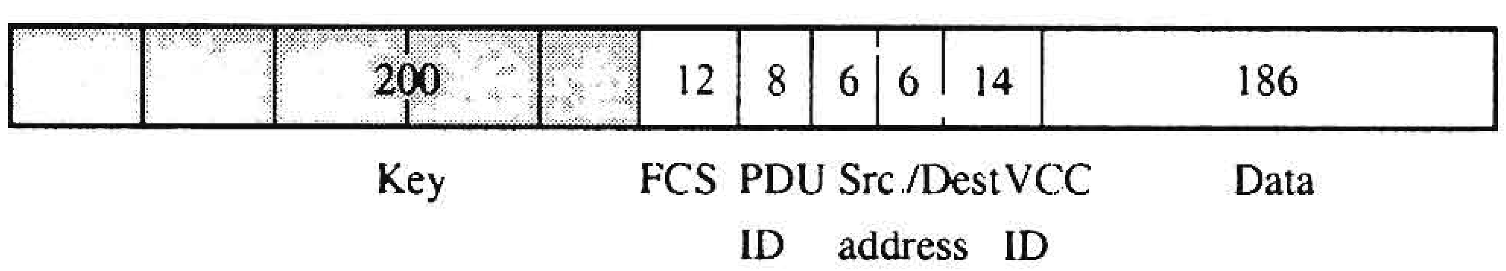

Fig 7 Acknowledge PDU

will reach S_1 safely and vice versa with a high probability (This procedure is similar to the RTS/CTS scheme used with IEEE 802.11 where a station transmits first a request-to-send (RTS) packet to the receiving station and waits for its acknowledge by a clear-to-send (CTS) packet) Both

[7] Carrier-Sense Multiple Access / Collision Avoidance

PDUs are recognized by the stations within the detection range of S_1 and S_2 and all stations in the receive range of S_1 and S_2 are aware of the TCH being in use as soon as station S_1 is transmitting on the respective channel.

Besides management related information an updated channel list from station S_2 is transmitted within the data field of the ACK PDU This provides station S_1 with information to identify other free channels for communication with station S_2.

The key contained in the ACK PDU of station S_2 serves to establish the TDD back-channel of station S_1 free of collisions. The key is able to eliminate the rare event that another station S_4 that is close to S_2 also has decided to transmit an ACK PDU in answer to a channel request of a station S_3, cf Fig 8

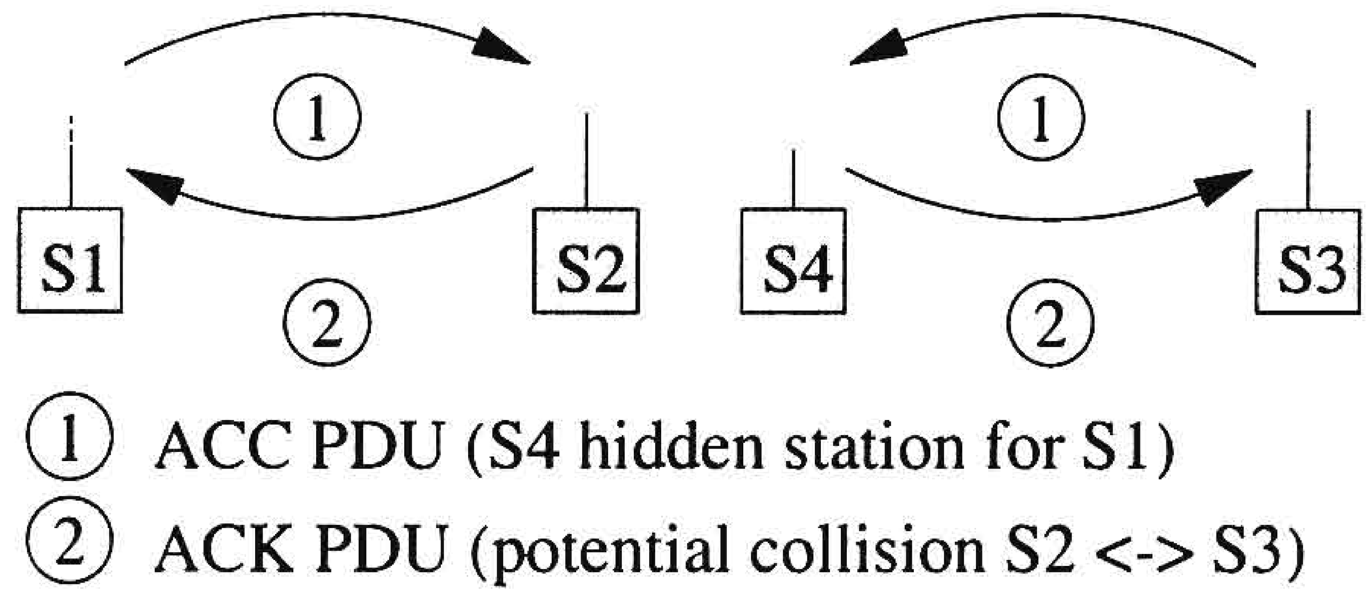

Fig 8 Collision avoidance during RCC establishment

This might happen when a hidden station S_3 has successfully transmitted its access PDU to station S_4 at the same time as S_1. If S_4 is also a hidden station for S_1 or the ACC PDU of S_1 has been captured by the ACC PDU of S_3, S_4 will respond to the ACC PDU of S_3.

If station S_1 collides during its initial attempt or it will not receive an answer of S_2, it will repeat the ACC PDU later The collision probability on the ACH can be guaranteed to be very low by dynamically defining the number of ACHs used Nevertheless, a decentrally controlled number splitting algorithm [16] might be applied to prevent from potential instability and reduce RCC establishment delays. If station S_2 has no free channel available matching the channel set proposed by S_1, it will answer on the ACH and propose another set of channels to S_1. A positive, negative, or no answer of station S_2 will be recognized by the stations in the transmit range of S_2. All channels having been reserved temporarily for a duration T_{res}, but the one selected by S_2 will now be marked free internally in these stations. It might be that a station 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 station soon will measure the allocated TCH in use in a TDD mode of operation. Thereby, all stations in the receive range of S_1 will detect its usage and release all the other channels reserved for the duration T_{res} and mark the used channel as occupied. 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.

For the procedure that has been described before it is assumed that on request of a new RCC at least one TCH can be found. To support QoS even for a highly loaded network where all TCHs are in use, established RCCs with low priority can be interrupted in favour of connections with higher priorities as described in Section IV-B.

D. Data transfer

After an RCC has been established, the data transfer is started. The packets that have in this design the size of the payload of an ATM cell, are transmitted transparently as payload of the data PDU, cf. Fig. 9, and are acknowledged on the backward channel.

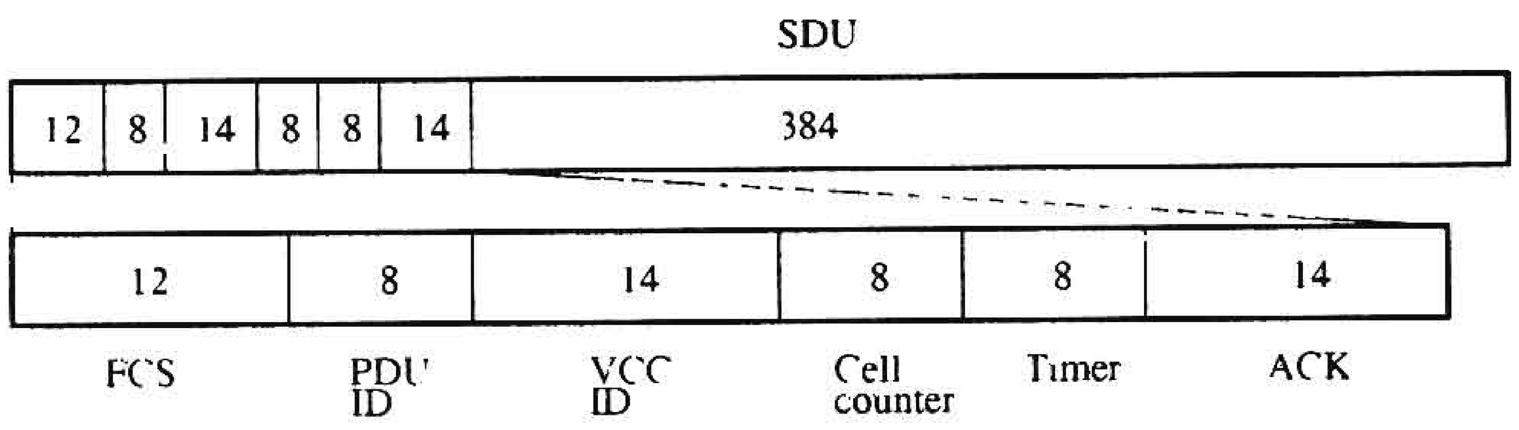

Fig. 9. Data PDU

Next to the cell counter of 8 bit and acknowledgements (ACK) of 14 bit for the ARQ protocol, the VCC-ID is transmitted within the PDU to allow statistical multiplexing of different VCC on the same RCC. Furthermore, the PDU comprises timing information (Timer) that determines the residual life time of the PDU and supports prioritized scheduling of urgent cells in intermediate stations of a route.

All other stations in the receive range of the respective stations will recognize and respect the occupancy of the channel through measuring the signal strength and a collision free transmission with guaranteed QoS becomes possible. Time division duplexing (TDD) on the same frequency is advantageous compared to frequency division duplexing (FDD), since all stations in the receive range of a station and node are able to detect the occupied channels without scanning the system frequency bands.

The number of time slots allocated to an RCC can be dynamically changed according to the actual needs of the communicating stations by transmitting a signalling PDU instead of a data PDU (see Fig. 10).

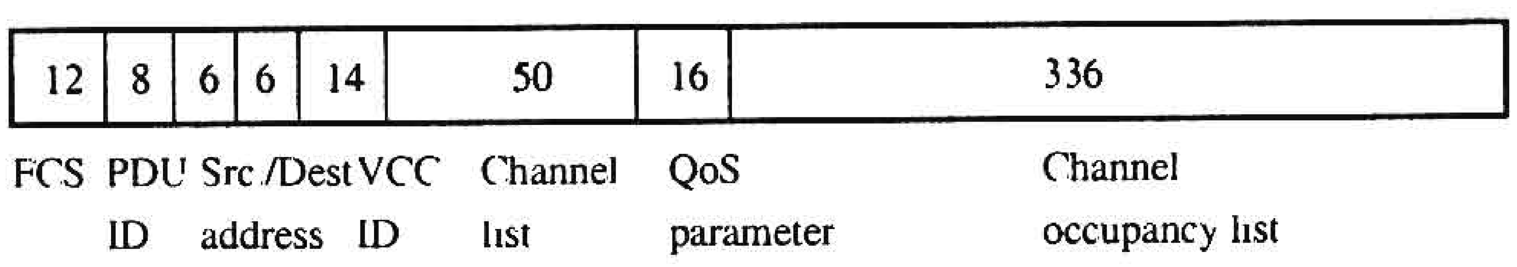

Fig. 10. Inband RCC signalling PDU

This PDU contains the same information as an ACC PDU and therefore can be used to increase the capacity of an active RCC or set-up a new RCC to a different destination station. Instead of the access key the current view of the station regarding the occupancy of the TCHs (e.g. reserved TCHs and respective RSSI values) are transmitted. This information is used by all receiving stations to update their routing tables and to temporarily reserve the proposed channels in the channel list. By this procedure, changes of the capacity of an one-hop connection can be performed in a very short time e.g., to allow to multiplex traffic of multiple VCCs to an RCC and to make quality of service re-negotiation very easy to introduce. This especially becomes important for real-time services with bursty traffic characteristic, e.g. video applications. 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.

D.1 Error control

To guarantee a very low residual packet error probability the logical link control (LLC) layer applies an ARQ protocol on a per hop basis. The data PDU contains 14 bit for piggybacked acknowledgements and another byte for a sequence counter. If no data has to be transmitted on the reverse channel that can carry the ARQ information a signalling packet is transmitted instead that carries additional ARQ information and the channel occupancy list as described before to update the routing tables (cf. Fig. 11).

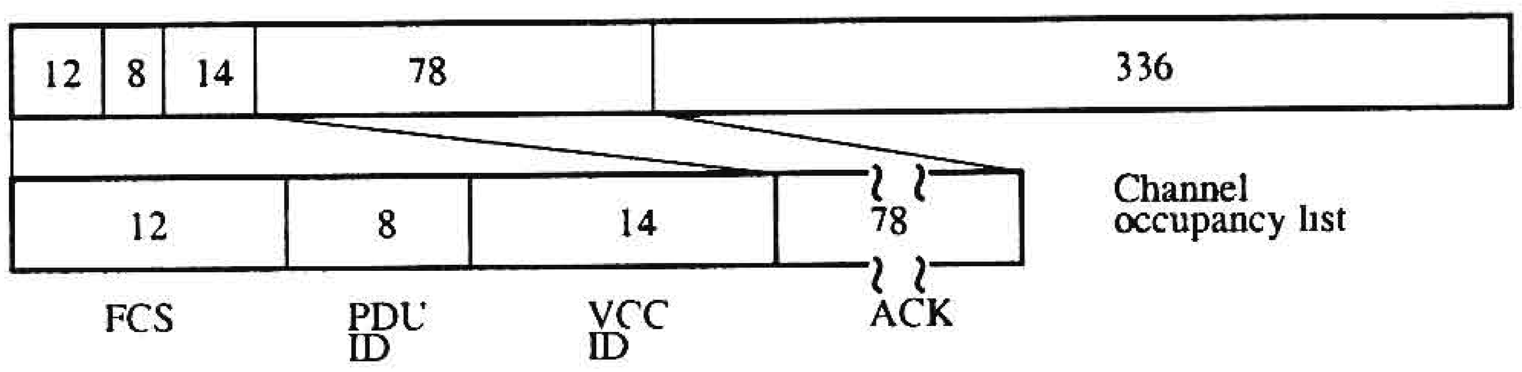

Fig. 11. ARQ signalling PDU

To improve efficiency of ACK reception, the multiple ACK protocol described in [17] can be used also.

D.2 Asymmetric traffic load

Under symmetric traffic load each slot is used alternating to carry forward and reverse traffic in a TDD mode of operation. To support asymmetric traffic flows, any relation of forward-to-reverse usage of a slot may be agreed per hop by the communicating stations, e.g. 8:1 would assign eight times the capacity forward, compared to backwards. To increase/decrease the relation of forward-to-reverse slots the signalling information will be transmitted over the RCC piggybacked with a data PDU. The receiving station will acknowledge the next higher/lower relation inband by the next packet. The resulting relations are given by

$$2^n\ 1 \underset{\text{decrease}}{\overset{\text{increase}}{\rightleftarrows}} 2^{n+1} . 1, \qquad n \in [0,3]. \qquad (1)$$

If a request for an increase of the forward-to-reverse relation would reduce the capacity of the backward channel below what is acceptable to the respective station a new TCH is reserved instead.

A threshold for the number of packets in a queue is used to decide whether a new TCH is needed instead a change of the forward-to-reverse relation. This guarantees that first the TDD mode is optimized to the asymmetric traffic and thus the reserved capacity is fully exploited.

E. Connection release of RCCs

Bursty traffic sources tend to use a channel as can be described by the packet train model [15], [18]. 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 stations involved in a hop, or by a decentralized decision from the other stations observing that the MAIG has been exceeded so that the respective slots are marked as free in their local channel occupancy 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 and the capacity for TCHs increased. A station is allowed to multiplex traffic of different applications and related VCCs to a given RCC to extend the train duration and reduce the number of accesses to the ACH.

F. Establishment of an end-to-end VCC

To establish an end-to-end virtual channel connection, an RCC will be requested with a new VCC-ID for an one-hop connection. The destination station can be retrieved from a station's local routing table that contains the one-hop next station for an end-to-end connection. If the RCC has been established, a connect request signalling PDU is transmitted to the one-hop (next) station that comprises the address of the end-to-end destination station. In case the addresses of the one-hop station and the end-to-end station are different, the station stores the new VCC-ID and the quality of service parameters and relays the connect request to the next station on the multihop connection. The destination station will respond with a connect confirm PDU that will be relayed by the intermediate station(s) to the source station and the new VCC is established then.

To protect the existing VCCs and to avoid the situation that the network will be overloaded, each station involved in the set-up procedure performs connection admission control, as explained in section VI, and rejects the connection request if sufficient capacity is not available.

IV DECENTRAL CAPACITY ASSIGNMENT CONTROL FOR QOS GUARANTEE

A. Prioritized access

To support both continuous and real-time variable bit rate (CBR, rt-VBR) services, which have stringent real-time requirements, opposed to other services (available bit rate, ABR, unspecified bit rate, UBR), which are much less sensitive to a time variance of throughput and delay, sets of keys for access PDUs representing different priorities are provided. The key contained in an access PDU 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. ABR and UBR service classes are assigned low priorities. If a station 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.

B. Requested release

It might be that a station S_1 having established a VCC but having released an RCC due to a pause in communication needs to re-establish an RCC to a station S_2 but is unable to name silent TCHs in its access PDU as candidate channels to be used. Station S_1 will then check all RCCs it is currently operating for low priority service classes and will select one and propose its TCHs for a new RCC to station S_2. To establish the new RCC to S_2 the respective TCH(s) between S_1 and the current neighbour station is(are) interrupted by S_1. In case no interruptable TCH is found by station S_1 the same procedure will be initiated by station S_2 when having received an access PDU from S_1 on the ACH. Station S_2 then will check all the RCCs it is currently operating with respect to the service classes they are supporting. In a responding PDU from S_2 transmitted on the interrupted TCH, station S_1 is informed about the new RCC to be used between S_1 and S_2. Trains with a higher (service class related) priority thus will be able to interrupt lower priority services on a per-hop basis. An interrupted RCC will be allowed after a service class specific delay T_s to try a re-establishment.

C. Forced release

To allow high priority services to find a free TCH whenever needed (re-establishment or increase of the number of TCHs for an active RCC), at least one TCH per hop is reserved for the service class with the highest priority.

When this channel will be accessed by a station with the respective priority, a station running a connection with a lower priority forced to release a TCH to always have one free TCH available. A similar approach is described in [19]. This requires to decentrally organize the forced releases of TCHs. As long as all stations involved have stored the service classes for each reserved TCH, the TCH with the lowest service class and with the longest life-time can be released. This approach is equivalent to a FIFO (first-in first-out) strategy for the lowest-priority service and tries to serve all stations in a fair manner by avoiding that one station continuously transmits its low-priority data while other stations can not find free TCHs or have to release the TCH after a short time in favour of requests of higher service classes.

But as long as a station is not aware of the services classes of the TCHs reserved before, because the respective stations are outside the decoding range, this station might be the only station that supports the lowest service class and therefore has to release its TCH when the last available TCH is used by a station with a higher priority In this case, all stations that have no knowledge of the services classes of the other TCHs and support low priority services classes have to release one TCH Still, the released TCH may not be usable for another station since its view of the interference situation is different

From this discussion it becomes clear, that a combination of the forced-release and requested-release approach should be considered to support time delay sensitive service classes

V POWER SAVING

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

VI 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 (VCC) before transmitting their user data Before opening a new connection the required capacity is therefore compared with the available capacity at the station All VCCs operated at stations within the detection radius and the new VCC are taken into account and make up an equivalent capacity C_{new}. If this capacity is below the total capacity C_{total} that can be provided by the station involved, the new connection is accepted [20] A new virtual end-to-end connection will be accepted if this procedure is successful on all the hops involved

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 be able to guarantee them at least some minimum average throughput.

Since routing in the network is much more efficient due to short addresses when VCCs are used, we apply VCCs for all types of services in the WANET

VII. PERFORMANCE RESULTS

The protocols described above have been analyzed by means of event-driven stochastic simulation Different radio connectivities for 20 stations 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 stations reached in one radio hop, normalized by the number of all the other stations N,

$$c = \frac{1}{N \cdot (N-1)} \cdot \sum_{i=1}^{N} n_i, \tag{2}$$

where n_i is the number of neighbours to station i For a fully meshed network the connectivity is 1.

Stations once for ever randomly select their final destination station and service class and establish the respective VCC No signal fading is taken into account; the packet error ratio (for all PDUs) is set to 1 % instead. The stations are assumed to have identical source traffic behaviour and to 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).

For the simulation study, the maximum allowed inter-cell gap is assumed to be two frames.

Figure 12 shows the payload throughput over the traffic load for networks with connectivity 1 0, 0 77, 0.57 and 0.5 for source 2

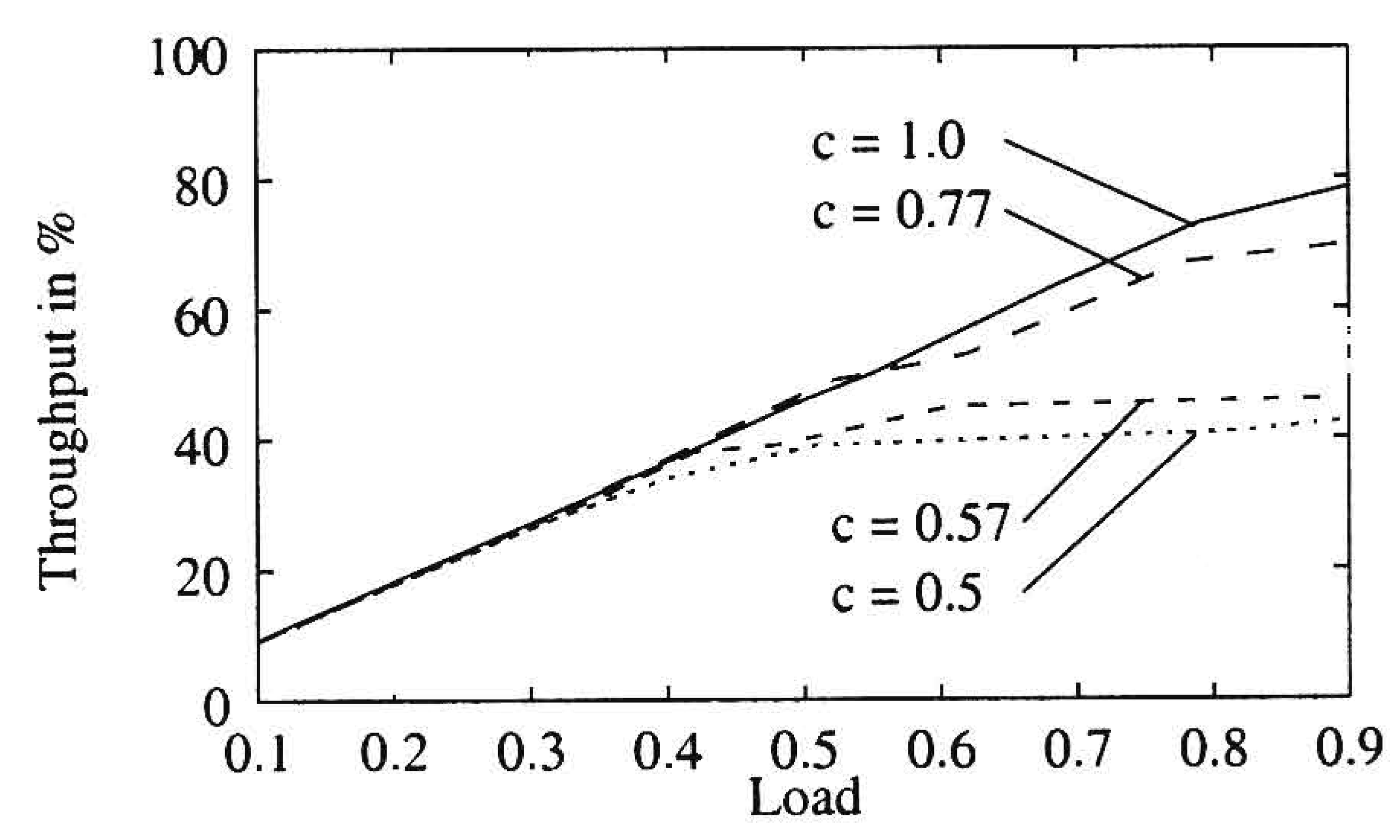

Fig 12 Throughput vs offered traffic for source 2

The offered traffic load results from the payload (ATM cells) only and is related to the available transmission capacity of 20 Mbit/s. Owing to the protocol overhead at the air interface the payload throughput is more limited the lower the connectivity is. With a connectivity of 0.5 the network is saturated for an offered traffic of 50 % of the transmission rate. A mean number of 1.9 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, cell trains typically consist of a continuous stream of data PDUs and one-hop connections are released after each packet. Throughput linearly increases with load until saturation is reached.

The end-to-end mean cell delay of source 2 packets shown in Figure 13 is nearly constant until the network approaches saturation. The number of TCHs for each RCC have been increased dynamically with load in this simulation experiment to keep delays small With loads approaching net-

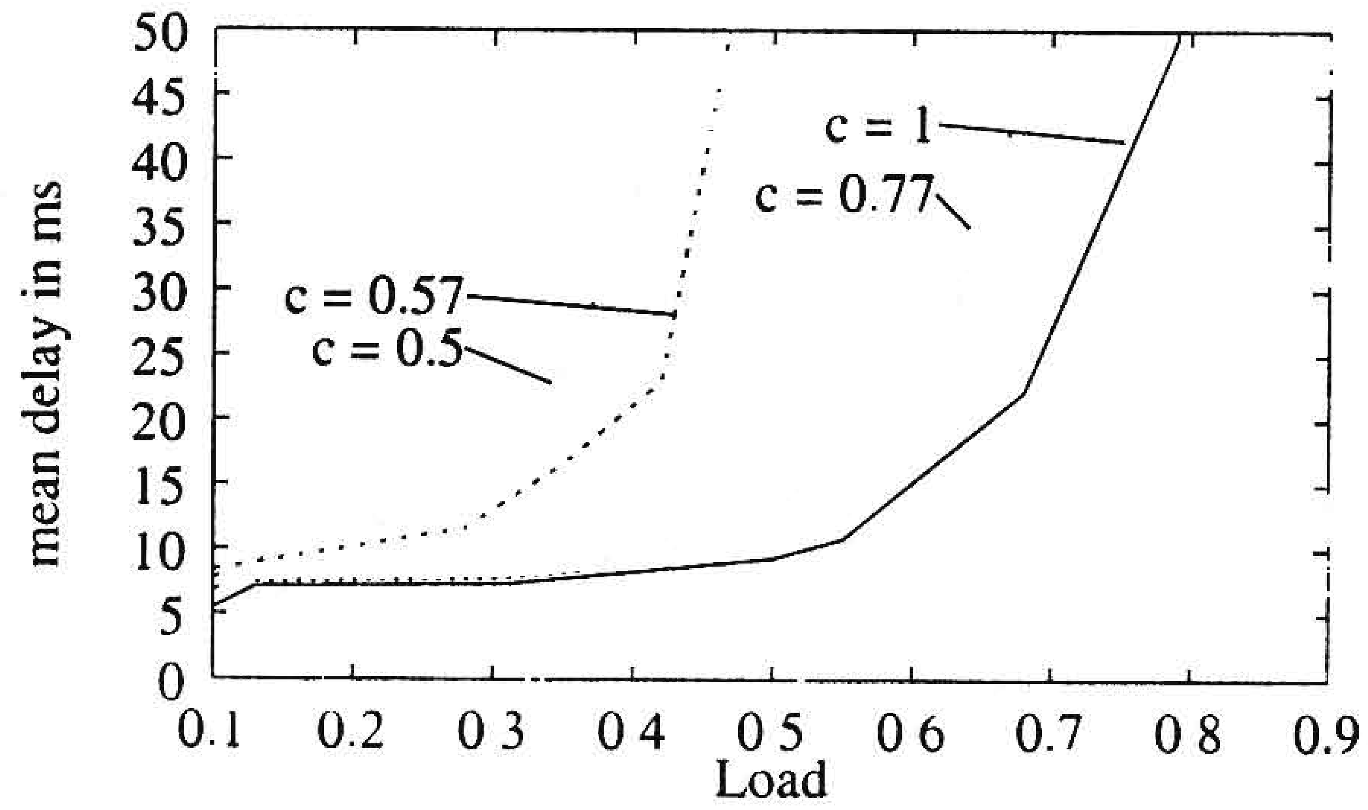

Fig 13 End-to-end cell delay vs offered traffic for source 2

work saturation the cell delay increases substantially as queueing in buffers is then dominating.

The delay can be reduced under small to medium load by allocating traffic channels based on more slots, e g TCH x/1, cf. Fig 14.

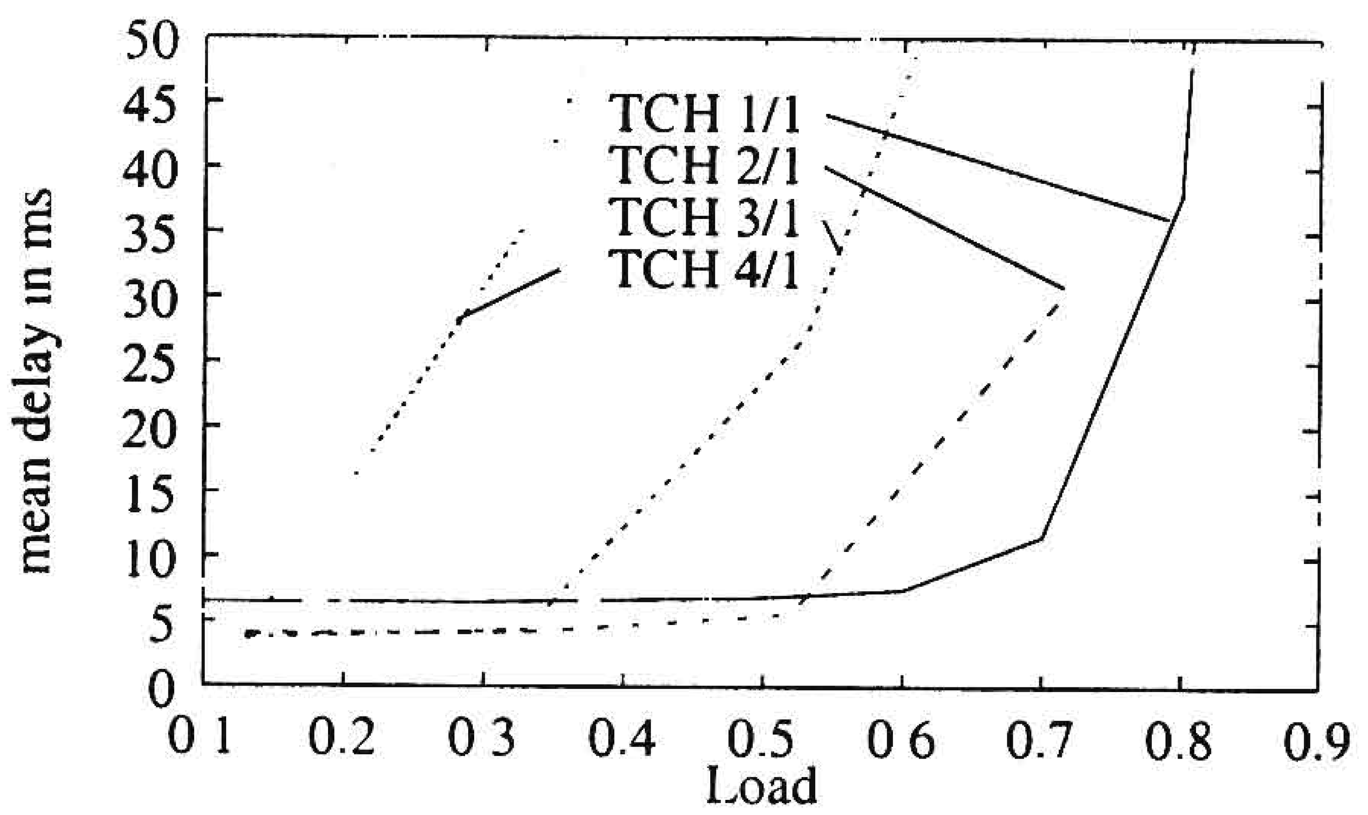

Fig 14 End-to-end cell delay vs offered traffic for source 2, c = 1 0

Using a TCH 4/1 for an RCC only 4 active RCCs can be supported simultaneously for a frame size of 16 slots. The mean delay under small load is reduced then, since arriving packets are served by a high transmit capacity in a short time

The delay can be further decreased by increasing the number of ACHs enabling a quick reservation of TCHs especially for short train durations [15]. With increasing load the trains become longer and the number of re-establishments of RCCs decrease so that the number of ACHs can be reduced and the protocol will continue to operate in a stable condition.

VIII Conclusion

A self-organized wireless ad hoc network supporting multihop operation with guaranteed QoS has been presented Using channel connections based on a TDMA frame, contention free data transmission can be realized by so called real channel connections (RCCs). RCCs in combination with the proposed access control protocols provide high throughput and a small delay even when hidden and exposed stations exist.

Performance results indicate that the end-to-end mean delay of cells can be kept nearly constant until the network saturation is reached, when the capacity of TCHs for each RCC is increased dynamically with its load.

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