An Air-Interface for Ad Hoc Networks Supporting High Mobility

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Abstract: **In this paper, a novel air-interface is presented for FleetNet[1], a self-organizing network for inter-vehicle and vehicle-to-roadside communication. The air-interface is based upon the low-chip-rate version of UMTS/TDD. To adapt the cellular UMTS standard to an air-interface for ad hoc networks, changes of the physical layer, medium access control sub-layer and radio resource management are required. An overview of the required modifications is given here. Particularly, a decentralized synchronization mechanism is presented and analyzed by means of simulations. Furthermore, changes for the medium access control are explained in detail, which allow for an efficient operation in partly meshed networks and prioritization. Performance results of the overall system considering throughput and delay are derived by means of analytical evaluations and event-driven simulations. Based on realistic mobility models, it is shown that the presented solution provides a robust communication platform even in vehicular environments. The proposed air-interface is a cost-effective solution not only for inter-vehicle communication, but also for ad hoc networking in general, benefiting from the mass-market of UMTS.**

Index Terms: **Inter-vehicle communication, MAC, performance simulation, RRM, synchronization.**

I. INTRODUCTION

Intelligent transportation systems (ITS) have attracted major attention during the last few years and vehicles have become a comfortable environment equipped with numerous electronic devices that alleviate the journey [1], [2]. Thus, it is anticipated that in the near future many vehicle manufacturers build multimedia devices into their vehicles for communication into and between vehicles. Typical envisaged applications comprise emergency warnings for security enhancement, collection and distribution of traffic-related information as well as applications like Internet access and interactive games. Initially, those systems will be found in high-end models, but it can be expected that they will become a standard equipment in future vehicles.

The FleetNet project, which is the framework of the technical content of this paper, aims at developing an ad hoc network for inter-vehicle communication (IVC) enabling ITS services. The main focus, therefore, is the selection of an appropriate air-interface for IVC, and incorporating slight modifications to come up in a very short time with a cost-effective and suitable solution, avoiding the time-consuming specification of a new air-interface. The most promising candidate is the UMTS terrestrial radio access time division duplex (UTRA TDD) system specified by 3GPP [3], as it will be shown in Section II. However, this cellular system has not been specified for IVC and, hence, it has to be modified to fulfill the requirements of a vehicular ad hoc network.

In Section II, it will be explained which changes have to be conducted with respect to the existing UTRA TDD standard specifications in order to fulfill these requirements. The changes comprise the physical layer, particularly synchronization mechanisms for a slotted and framed system, which will be presented in Section III. In this section, it will also be demonstrated that the physical layer of UTRA TDD outperforms alternative air-interfaces. In Section IV, the changes to the medium access and radio resource control will be explained. The ad hoc routing protocols, developed within the FleetNet project, are briefly presented in Section V. Finally, a performance analysis of the air-interface is presented in Section VI. The analysis is carried out with respect to throughput and delay by means of analytical and simulative investigations.

II. THE FLEETNET AIR-INTERFACE

The philosophy of FleetNet is to exploit an existing air-interface and incorporate slight modifications to come up in a very short time with a cost-effective solution that benefits from a mass-market. Hence, the most obvious solution is the reuse of an existing cellular system, e.g., like it is proposed in [4]. However, time crucial key applications, e.g., driver assistance applications require a peer-to-peer communication. Particularly, safety applications should not rely on the availability of a cellular infrastructure. Furthermore, the amount of data to be exchanged between vehicles would congest a centralized network in heavy traffic conditions.

Systems that support self-organization such as the wireless local area networks (WLAN) IEEE 802.11 or HIPERLAN/2 [5] neither support the required large communication distances of more than 1 km nor allow for operation at high velocities of up to 500 km/h [6]. Within the standard IEEE 802.11a/RA (road access) the guard-interval of the orthogonal frequency division multiplexing (OFDM) scheme has been doubled compared to IEEE 802.11a to increase the multipath resistance and to combat higher Doppler-spreads [7]. However, high operation frequencies at 5 GHz have a strong effect on the radio range and

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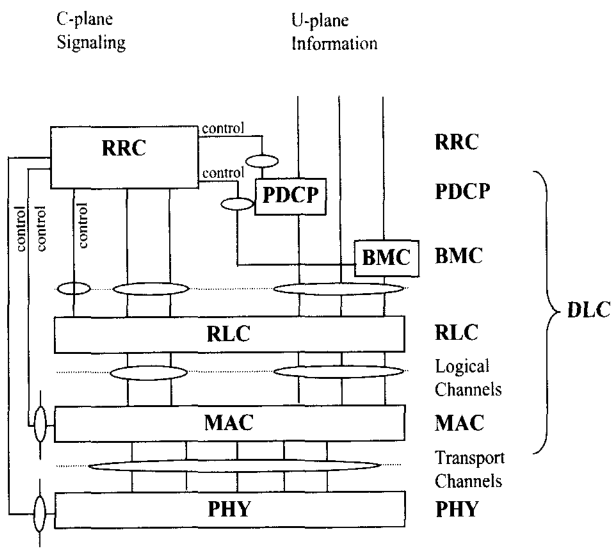

Fig. 1. Air-interface protocol architecture. The service access points are marked by circles.

speeds up to 250 km/h as allowed on German highways are still a big challenge with respect to inter-channel interference. For HIPERLAN/2, fast network organization and reorganization is a major problem due to its centralized organization. In addition, it incorporates the same challenges as IEEE 802.11a/RA. Moreover, frequency bands for the operation of IEEE 802.11a/RA have only been allocated so far in the USA by the FCC. Further channel assignment by European regulatory bodies like CEPT is not planned. The air-interface meeting the FleetNet requirements best is UTRA TDD [8]. One argument is the availability of an unlicensed frequency band at 2010–2020 MHz in Europe. Others are that UTRA TDD offers high flexibility with respect to asymmetric data flows and granularity for data transmission because of its code division multiple access (CDMA) component. Furthermore, it supports quality of service (QoS) since it is possible to reserve transmit capacity owing to its frame and slot structure. In addition, it allows communication over large distances and supports high velocities. In contrast to systems based on a WLAN standard, UTRA TDD was designed for a multipath propagation environment. Since UTRA TDD was initially developed for operation in a cellular network structure, some modifications are required for an ad hoc operation. Besides the changes to medium access control (MAC) and radio resource management (RRM), also some modifications of the physical layer are required to allow for an ad hoc operation. UTRA TDD comprises a low chip rate (LCR, 1.28 Mchip/s) and a high chip rate (HCR, 3.84 Mchip/s) option. Since the LCR option is close to mass-market introduction, it was chosen for the FleetNet air-interface. However, the approach for the integration of an ad hoc mode can easily be adapted to HCR.

A. Radio Interface Protocol Architecture

The air-interface protocol stack of UTRA TDD is divided into three layers: The physical layer (PHY), the data link control layer (DLC), and the network layer (NL), see Fig. 1.

The physical layer (PHY) of the LCR mode defines a radio frame of 10 ms duration, which is divided in two sub-frames consisting of 7 time slots, respectively [9], see Fig. 3. Following the first time slot, a special slot for synchronization is inserted, which is 275 μs long. Each of the regular time slots has the same length and contains the UTRA TDD LCR traffic burst, consisting of two data symbol fields of 352 chips, a midamble of 144 chips and a guard period of 16 chips. UTRA TDD allows the usage of different channelization code lengths (spreading factor, SF: 1, 2, 4, 8, 16), which enables the parallel transmission of up to 16 codes in one time slot [10].

The medium access control (MAC) layer maps the logical channels of the RLC onto the transport channels supported by the physical layer. The priority handling between different data flows, which are mapped on the same physical resources, is also part of the MAC layer.

The radio link control (RLC) layer provides transparent, unacknowledged or acknowledged mode data transfer to the upper layers. The main functions of the RLC are ciphering of data in acknowledged or unacknowledged mode and the support of an automatic repeat request scheme (ARQ) in acknowledged mode.

The broadcast/multicast control (BMC) layer exists in the user plane (U-plane). In the UTRAN, there is only one BMC entity per cell providing the services for cell broadcast. The packet data convergence protocol (PDCP) is present in the U-plane only. It provides header compression functions for network protocols, i.e., the Internet protocols IPv4 and IPv6.

The radio resource control (RRC) layer as part of the NL handles the control plane (C-plane) signals between the UTRAN and the user equipments (UEs). It is also responsible for controlling the available radio resources. This includes assignment, reconfiguration and release of radio resources as well as continuous control of the requested QoS.

III. PHYSICAL LAYER OF UTRA TDD AD HOC

In the following sections, an overview of the physical layer of UTRA TDD ad hoc will be presented: Besides the frame and burst format, the modifications compared to the cellular mode of UTRA TDD are discussed. In particular, the synchronization mechanisms required to allow an ad hoc operation in vehicular environments with high velocities are presented and their performance is analyzed.

A. Modifications for Ad Hoc Operation

Frame and burst structure

The ad hoc mode of UTRA TDD uses the same frame and burst structure as the cellular mode of the LCR option. The main difference to the cellular mode is the restriction that only one station is allowed to transmit at one time, and consequently, only one midamble is received in each burst.

Multiplexing of user data to a single burst

In the UTRA TDD standard, a PHY service data unit (PSDU) is always interleaved and multiplexed over multiple bursts. To meet the requirement of low latencies for high priority data packets (e.g., for emergency notifications), it necessary that the

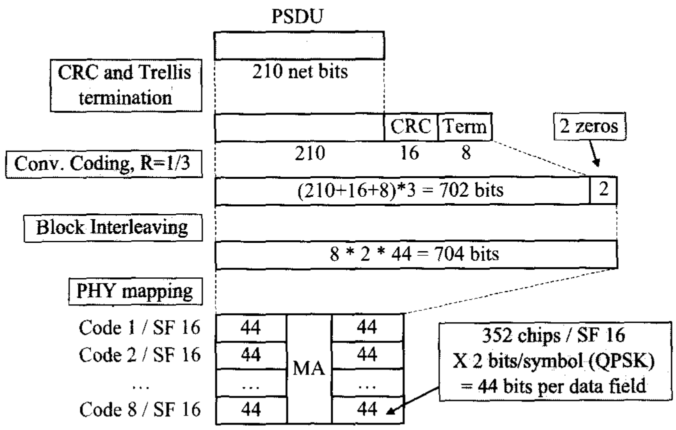

Fig. 2. Multiplexing of data to single burst.

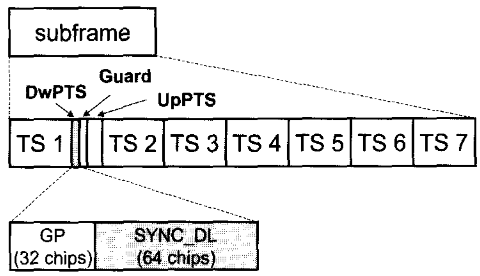

Fig. 3. Position of DwPTS within sub-frame.

PHY provides the functionality to transmit and receive data packets in a single burst. Therefore, new multiplexing schemes for mapping of user data to a single burst have been defined. A multiplexing example of a PSDU for UTRA TDD ad hoc is depicted in Fig. 2. Here, a PSDU contains 210 net bits that are mapped to 8 parallel codes with a spreading factor of 16, respectively.

Synchronization

In the cellular mode of the 1.28 Mcps option of UTRA TDD, frequency and chip synchronization can be derived from the downlink pilot time slot (DwPTS) [11]. The DwPTS field has a fixed position within a each sub-frame (see Fig. 3) and is sent out only by the base station, periodically.

In order to enable a decentralized time synchronization of the mobile nodes in the ad hoc mode, the broadcasting of the DwPTS is performed by the mobile nodes themselves. In this case, all nodes within the network are allowed to transmit a SYNC_DL sequence. Since a mobile station is not able to receive signals during own transmissions, nodes randomly leave out own transmissions of the SYNC_DL sequence in order to measure the timing of other mobile stations. The UTRA TDD ad hoc PHY synchronization consists of two main parts: A coarse time synchronization and an additional fine synchronization. The details of the two schemes will be presented in the following two sections.

B. Coarse Time Synchronization

Because of the time slotted radio frame structure, it is required to apply a certain timing for the transmissions to avoid an overlap of user bursts and to align all stations to the commonly used frame structure.

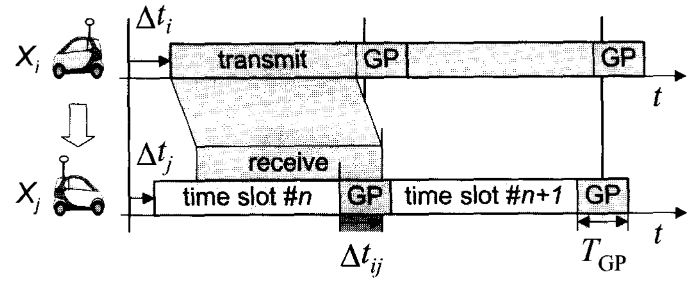

Fig. 4. Observed time offset at node X_j.

B.1 Timing Requirements

Fig. 4 illustrates the time offset observed at a node X_j for a transmission of a node X_i: Nodes X_i and X_j have an absolute time offset of Δt_i and Δt_j, compared to a global time reference, respectively. An observed time offset Δt_{ij} of a burst, transmitted by X_i and received at node X_j can be calculated by:

$$\Delta t_{ij} = \Delta t_i - \Delta t_j + \frac{d_{ij}}{c}, \tag{1}$$

where d_{ij} denotes the distance between both nodes and c is the speed of light, resulting in the propagation delay $\Delta t_{\text{prop}} = d_{ij}/c$. To ensure a reception of bursts without an overlap, the absolute value of the observed time offset Δt_{ij} has to be smaller than the guard period T_{GP}:

$$\Delta t_{ij} \overset{!}{<} T_{\text{GP}}. \tag{2}$$

Mobile nodes that fulfill at least the timing requirement in (2) are called coarse time synchronized.

B.2 Decentralized Coarse Time Synchronization

The basic idea of the proposed decentralized synchronization scheme is to achieve a locally common slot and frame timing by a mutual adaptation of the individual node timing. The synchronization procedure consists of two steps: First, the timing of a received burst is acquired. In a second step, the own timing is adapted according to the observed time difference to the node that transmitted the respective burst.

Frame and slot timing acquisition

The timing acquisition to estimate the observed time offset Δt_{ij} of a received signal works as follows: In each time slot without own transmission (including the omitted downlink pilot time slot, DwPTS), the mobile node correlates the received signal $r[n]$ with the SYNC_DL sequence $s_{\text{SYNC\_DL}}[n]$:

$$\Psi_n = \sum_{k=0}^{63} r[n+k] \cdot s^*_{\text{SYNC\_DL}}[k]. \tag{3}$$

By finding the argument n that maximizes the absolute value of Ψ_n within the own slot boundaries, the observed time offset Δt_{ij} from node X_j to an arbitrary node X_i that transmitted during the current time slot can be estimated. To reduce the probability

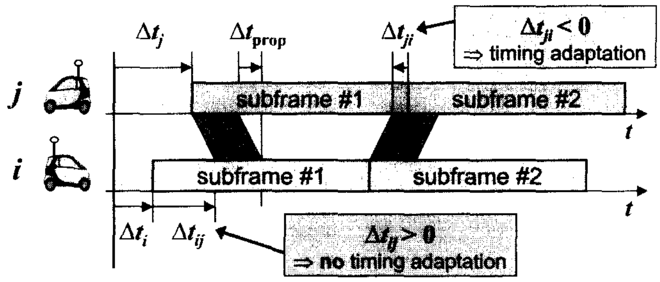

Fig. 5. Timing adaptation of node X_j.

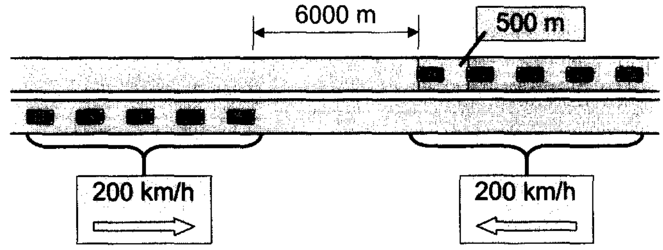

Fig. 6. Example simulation scenario.

to detect a position of the SYNC_DL, even if no sequence was transmitted (false-alarm probability), the normalized correlation coefficient R is calculated for the detected position n_0:

$$R = \sqrt{\frac{\Psi_{n_0}^2}{64 \cdot \sum_{k=0}^{N_{\text{SYNC\_DL}}-1} |r[n_0+k]|^2}}. \quad (4)$$

Only if the absolute value of the normalized correlation coefficient R is above a predefined threshold, the estimate will be processed. Extensive simulations have shown that a threshold of $R_{\text{Thres}} = 0.6$ is suitable. If more than one node simultaneously transmit a burst within the synchronization range of node X_j, the maximum correlation value is selected. This corresponds to the strongest (and in most cases to the closest) node X_i within the synchronization range of node X_j. An important fact for the decentralized synchronization is that the geographic range where a detection of the DwPTS is possible is much larger than the range of possible data decoding. As a result, approaching vehicle groups are able to mutually synchronize before both groups merge for communication.

Timing adaptation

At the end of a successful timing acquisition phase described in the last section, each node X_j adapts its own slot timing Δt_j according to

$$\Delta t_{j,\text{new}} = \begin{cases} \Delta t_{j,\text{old}} + w \cdot \Delta t_{ij} & \text{if } \Delta t_{ij} < 0 \\ \Delta t_{j,\text{old}} & \text{else} \end{cases}, \quad (5)$$

where the parameter w denotes a weighting factor that determines the stability and convergence behavior of the algorithm. By choosing an appropriate value of $w < 1$, e.g., $w = 0.1$, a stable synchronization can be achieved. In order to maintain coarse time synchronization to nodes within the own group, the maximum allowed timing adaptation is limited to a fixed value $T_{\text{adapt,max}}$, which is smaller than the duration of the guard interval. For simulations within this paper, a value of 4 chips is used. An important fact is that according to (5), only negative observed time offsets Δt_{ij} are compensated. The reason to ignore positive offsets is that with each acquired time offset, not only the actual difference of the node timings is acquired but also the distance-dependant propagation delay, see (1). As a result, even if all nodes have a perfect initial time synchronization, a constant time drift will be observed since each node tries to compensate the measured propagation delay. By compensating only negative time offsets, this systematic drift of the node timings is prevented.

An example situation is shown in Fig. 5: In the first subframe, a positive time offset Δt_{ij} is acquired at node X_j and therefore no timing adaptation is initiated. In the second subframe, node X_j acquires a negative time offset, which will be compensated. In an adjusted state, the following equation holds:

$$\Delta t_{ij} = 0 \Rightarrow \Delta t_{ji} = 2\Delta t_{\text{prop}}. \quad (6)$$

Two arbitrary nodes are kept synchronous within a time interval of twice the propagation delay between them.

Performance evaluation

To analyze the dynamic synchronization behavior of a defined set of nodes realistically, a simulation environment has been developed, where each receive signal is calculated individually by superimposing all transmitted signals during the reception phase. Velocity-dependant frequency shifts as well as distance-dependant time shifts of transmitted signals are considered. For simulation, different scenarios have been defined, where each scenario models an extreme situation for the mechanism.

One of the most critical scenarios is shown in Fig. 6: Two separated groups of equidistantly spaced vehicles are approaching with a very high velocity of 200 km/h, respectively. Initially, both vehicle groups are completely unsynchronized: They are assumed to have the maximum possible timing offset of half a sub-frame duration. At the beginning of the simulation, the distance between both groups is large (6000 m) and communication is possible only within the respective group. Eventually, the gap between the groups becomes smaller and a mutual interaction starts. The challenge is to achieve at least a locally common timing between both groups without losing synchronization within the own group, respectively. The simulation ends, when both groups have driven past each other and their mutual distance is again 6000 m.

In Fig. 7, a statistical analysis of the simulation results is depicted: For each pair of nodes X_i and X_j, the observed time offset Δt_{ij} is analyzed every 10 ms during the whole simulation. The figure shows the statistical intervals, in which 95% of the observed time offsets are located, depending on the distance between X_i and X_j, quantized in intervals of 100 m, respectively. Additionally, the propagation delay for a transmission from X_i and X_j is depicted, for comparison. The dashed red line indicates the UTRA TDD timing requirement ((2)). It can be observed that the coarse time synchronization requirement is met for two arbitrary nodes with a distance of less than 1800 m. Since this is larger than the expected communication range of

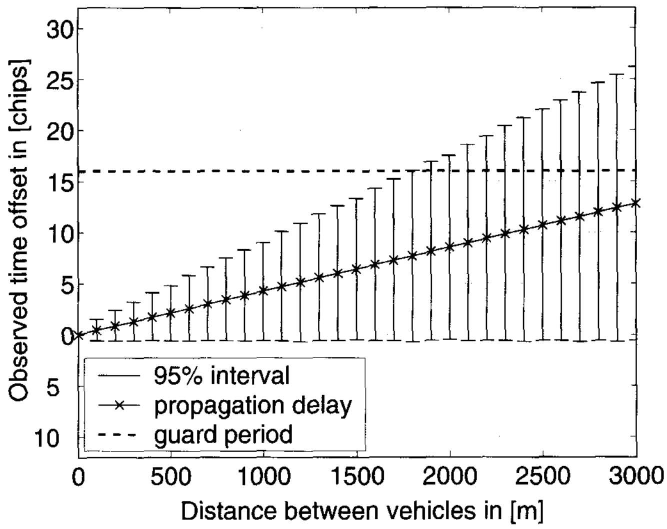

Fig. 7. Decentralized synchronization performance.

1500 m, synchronization is achieved before the groups merge. This is possible because of the large spreading factor of the synchronization sequence: The range in which synchronization information is detected is approximately twice the communication range, and thus, the timing adaptation starts long before the two groups are in communication range. Like predicted in (6), the observed time offset to an arbitrary node has a maximum value of approximately twice the propagation delay.

C. Fine Synchronization

FleetNet nodes receive data bursts with several time offsets, caused by different propagation delays and imperfect coarse time synchronization. Furthermore, received signals are subject to carrier frequency offsets (CFO), caused by local oscillator inaccuracies and Doppler shifts due to high relative velocities between FleetNet nodes. In order to be able to detect and demodulate a received burst without any prior knowledge of the transmitting station, a one-shot synchronization is required to refine the coarse time synchronization and to estimate and compensate occurring carrier frequency offsets.

C.1 Chip Synchronization

In UTRA TDD, training sequences (midambles) are contained in each transmitted burst. Basically, they are used to estimate the channel impulse response of the mobile radio channel and are chosen to have good aperiodic autocorrelation properties. Therefore, the cross-correlation of the input signal with the reference midamble is used for chip synchronization. An important fact is that because of the preceding coarse time synchronization (Section III-B.2), the search area for the midamble can be reduced to an interval of twice the length of the guard period (GP).

C.2 Frequency Synchronization

To estimate the carrier frequency offset of the received burst, a maximum likelihood technique is applied to the midamble part of the received signal. In the case that both frequency and phase of a received signal are unknown, the maximum likelihood frequency estimate under the assumption of additive white Gaussian noise (AWGN) is

$$\hat{\Omega}_0 = \arg\max_{\Omega} \left| \sum_{n=0}^{N_{\text{midamble}}-1} \tilde{m}[n] \cdot e^{-j\Omega n} \right|^2 = \arg\max_{\Omega} I_{\tilde{m}}(\Omega), \quad (7)$$

where

$$\Omega = 2\pi f T_{\text{Chip}}, \quad (8)$$

is the normalized frequency and $I_{\tilde{m}}(\Omega)$ is the periodogram of the time-discrete sequence $\tilde{m}[n]$, with

$$\tilde{m}[n] = m[n] \cdot m^*_{ref}[n]. \quad (9)$$

A maximization of the periodogram can be performed using an iterative search procedure with low computational complexity, which is proposed in [12]. In cases of strong multipath propagation, the received midamble will be affected by intersymbol interference (ISI) and as a result, the maximizer of the periodogram does not necessarily approach the actual CFO with increasing SNR values. To overcome this situation, an additional frequency refinement (AFR) is applied that reduces the residual frequency error after frequency synchronization [12].

IV. MEDIUM ACCESS IN UTRA TDD AD HOC

Within 3GPP, an ad hoc mode called opportunity driven multiple access (ODMA) was proposed for UTRA TDD [13]. Different spreading codes and power control are used to cope with changing topologies and hidden-stations. However, due to its requirement of a central authority, ODMA is not suited for FleetNet. A MAC protocol for a vehicle-based ad hoc network called decentral channel access protocol (DCAP) was investigated in the PROMETHEUS framework in the early nineties [14], which proposes a similar scheme as the one proposed here. It is based on a frame structure and reserves capacity by means of reservation ALOHA.

In the UTRA TDD ad hoc mode developed within the FleetNet project, transmit capacity at one frequency is provided by a combination of one or more time slots and one or more codes. Such a combination of frequency, slot, and code provides transmission capacity for one logical channel, which can be used as unicast, anycast, multicast, or broadcast connection.

To preclude the power-impairment problem[2] that is associated with a CDMA component[3] in an ad hoc network, it is proposed that only one station is allowed to transmit in one slot at the same time. With the proposed concept, several stations (up to the number of parallel codes that are supported, in case of UTRA TDD this number is 16) can be simultaneously reached by one station. The approach is equivalent to the downlink direction in a cellular CDMA system and, therefore, still exploits the

[2]The phenomenon that for specific transmitter-receiver constellations the near-far effect cannot be resolved by means of power control, is defined as the power-impairment problem.

[3]It is assumed that spreading is performed by a direct sequence (DS) resulting in a DS-CDMA system.

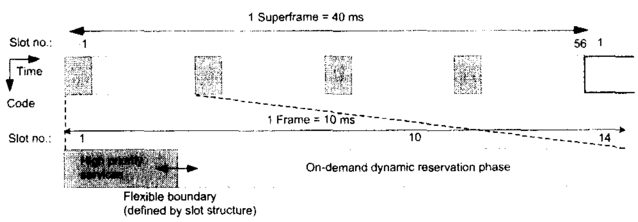

Fig. 8. Organization of the frame.

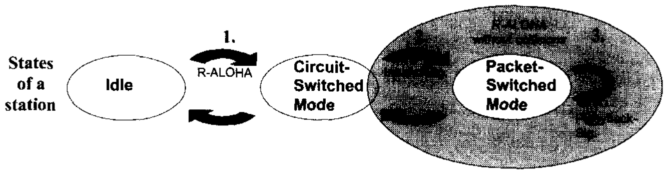

Fig. 9. States of the MAC protocol.

advantage of fine granularity of capacity offered by the CDMA component over a pure TDMA system.

Although the proposed concept of code assignment takes into account the code domain, it requires no closed loop transmit power control (TPC) for detection of codes that are transmitted in the same slot but with different spreading codes. Furthermore, a simple Rake receiver is sufficient for equalization and code separation, which reduces the hardware complexity at the receiver branch considerably. Another advantage of a TDMA system over, e.g., a pure FDD or a CSMA system is the possibility to reserve an exclusive part of the frame for high-priority services. Reservation of transmit capacity is a basic requirement for QoS guarantees. Different ways are foreseen for reservation: A certain part of the capacity in terms of slots in a frame is constantly reserved for high priority services. The remaining part, called on-demand dynamic reservation phase, can be dynamically assigned and temporarily reserved by different stations for several services with lower priority, cf., Fig. 8.

The boundary between the two parts is flexible but defined by the slot structure. The minimum number of high priority slots, N_{high}, is a system parameter and assumed to be $N_{\text{high}} = 1$ in the following.

A. Service Classes

In FleetNet diverse applications with different needs for QoS exist. The different reservation methods of the FleetNet MAC protocol cope with the different classes:

- Emergency notifications are of enormous importance. They do not occur often but when they occur, sufficient capacity must be available. Therefore, one time slot is constantly reserved for this service. Access to this high priority channel is performed by a simple random access scheme like ALOHA, which will not be considered in more detail in this paper.
- All other services may have delay or throughput constraints, but they are not as important as emergency notifications. Therefore, they share the remaining part of the MAC frame. The underlying services are called on-demand services in the following and will be the subject of the remainder of this clause.

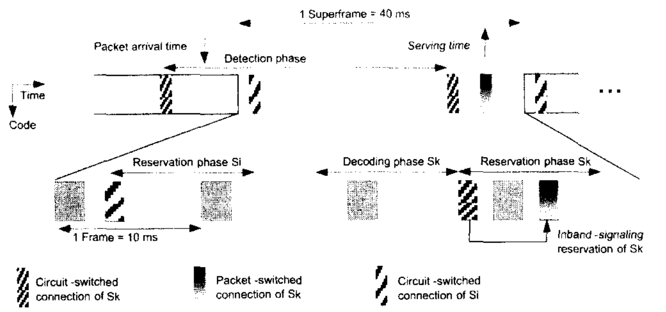

Fig. 10. Example for capacity reservation by means of inband-signaling.

Reservation ALOHA (R-ALOHA) is the basis for the reservation of capacity for on-demand services. It is well known that it has better performance than slotted ALOHA. Still, R-ALOHA has the potential risk of instabilities and may result in high collision rates for many participating stations and frequent reservation attempts, particularly in the case of short packets. Hence, a different reservation scheme shall be used where a certain share of the available capacity is permanently reserved, resulting in a so-called "circuit-switched" broadcast channel (CSBC). If the number of stations is not too high, each station reserves a CSBC. If the number of stations grows, only a certain ratio of them reserves a CSBC. All others use pure R-ALOHA. For initial reservation of CSBCs, R-ALOHA is used (cf., step 1 in Fig. 9). To reduce the amount of permanently reserved capacity, a superframe is introduced, which comprises a number of basic frames. In the following, it will be assumed that a superframe consists of 4 basic frames, resulting in a superframe duration of 40 ms (cf., Fig. 8).

B. Reservation of Transmit Capacity

If a station has data to be transmitted, it may use its CSBC. If this capacity is not sufficient, it uses the CSBC to transmit a reservation request for additional capacity (inband-signaling, cf., step 2 in Fig. 9). Reserved slots are sensed and will be respected by the neighboring stations. Packets transmitted in the same slot in subsequent frames can be described as packet train. The reservation for the used slot is maintained by piggyback signaling (cf., step 3 in Fig. 9) until the train ends and the slot is released. This results in a system behavior of R-ALOHA without collisions.

C. Connection Management

After a packet has arrived from higher layers, the station waits until its next CSBC slot is available to reserve transmit capacity in this or in the next frame. To avoid collisions with reserved slots of other stations, the usage status of all slots is measured before reservation. This decoding phase has the length of one frame duration (10 ms, 14 slots resp.) and helps to predict the usage status of the 14 slots in the following frame duration. In Fig. 10, the resulting frame structure and the usage of reserved slots is shown.

The reservation procedure of additional capacity is based on the knowledge which channels (time slots) are available, i.e., which are free of interference, and which are used (reserved) by other stations. This knowledge will usually be gained by a) measuring the radio channel, and b) receiving reservation packets from neighboring stations. Measuring the signal strength (RSSI, received signal strength indicator) of each time slot, a station can detect the status of each slot. If the RSSI is below a predefined threshold Th_{detec}, the channel is expected to be unused; if it is above Th_{detec} but below a second threshold Th_{decode}, it is assumed to be in use by other stations. If the signal strength is above Th_{decode}, the transmitted data can be decoded.

In the latter case, a station can obtain the IDs of the communicating stations, detect reservation messages and release flags, i.e., it can forecast the usage status in the following frames. This forecast is needed in the case when a station wants to reserve additional resources without disturbing foreign reservations. However, even without decoding messages, the future reservation of slots can be anticipated because of the frame and slot structure and the fact that used slots are automatically reserved in the next frame (principle of R-ALOHA). This is a fundamental advantage of reservation-based MAC schemes using a frame/slot structure compared to asynchronous schemes that use random-access, e.g., CSMA.

Due to node mobility and the presence of hidden stations, the knowledge of each station on the usage status of slots is not always complete. Hence, nodes may have reserved identical resources and packet collisions can occur. Collisions have to be resolved by reservation of new resources and lost packets have to be retransmitted, which leads to a degradation of system performance, i.e., packet delay and spectral efficiency.

If every station transmits its own knowledge on the channel status inside its CSBC in terms of a neighborhood table with channel status indicator (CSI), the system performance will improve. Instead of broadcasting information on the usage status of each available resource in the system (56 slots), a station will only transmit information on which resources it will receive from which sender. First, this will reduce size of the table and will avoid transmission of redundant data. Stations will receive CSIs from all surrounding stations and can combine them to a more complete knowledge. Second, packet collisions happen at the receiver, so information on successful receptions are much more important than on potential unsuccessful transmissions.

In [15], we evaluated and simulated this concept for an enhanced protocol version, exploiting more than one frequency channel, where even more possibilities of reservation conflicts exist. The results showed that the described protocol is well suited to decrease collisions and increase overall system throughput.

V. ROUTING

Routing in FleetNet has to cope with rapidly changing topologies, e.g., on highways where vehicles approach with relative velocities up to 500 km/h. Although routing in self-organizing networks is an important topic, it will not be the focus of this paper that mainly describes a novel air-interface for IVC.

Existing approaches can be classified in three categories: Proactive, reactive, and position-based algorithms. In proactive schemes, all nodes maintain routing information about the available paths in the whole network even if these paths are not currently used. Hence, proactive schemes do not scale well with network size, and frequent network changes will result in high traffic load caused by signaling messages used for route maintenance, making this approach unsuitable for FleetNet.

Reactive routing schemes, also called on-demand routing, establish and maintain only paths that are currently in use, thereby reducing the signaling traffic. Nevertheless, they have two inherent limitations when the topology changes as frequently as it does in FleetNet: First, even though less routes have to be maintained than in proactive approaches, route maintenance may still generate a significant amount of signaling traffic, and second, packets on their way to the destination are likely to be lost if the route to the destination breaks.

The last category, position based routing algorithms, eliminate some of the mentioned deficiencies of proactive and reactive algorithms. They only require information on the physical position of the participating nodes. A comprehensive overview and investigation is given in [16]. Since it can be expected that in the near future all vehicles will be equipped with GPS, this requirement is fulfilled within FleetNet. The forwarding decision in position-based routing is based on the destination's position contained in the packet and the position of the forwarding node's neighbors. Position-based routing, thus, does not require the establishment or maintenance of routes. The nodes neither have to store routing tables nor do they need to transmit messages to keep routing tables up-to date. As a further advantage, position-based routing supports the delivery of packets to all nodes in a given geographic region in a natural way, which is of high profit for typical applications, e.g., emergency warnings and traffic travel information. For these reasons, position-based routing algorithms will be used in FleetNet.

VI. PERFORMANCE ANALYSIS

The performance evaluation of the air-interface is divided in an analytical part to understand the basic behavior of the protocol and a simulative part that provides a more realistic assessment under varying load conditions. If not explicitly stated, the following assumptions are valid for all performance investigations: A frame with duration of $T = 10$ ms comprising $N = 14$ slots is considered, wherein $N_{\text{high}} = 1$ slot is permanently reserved for high priority services. Simultaneous transmissions of more than one station result in collisions. No capture-effect is taken into account. All M stations have identical message arrival statistics that follow a stationary Poisson process with a message arrival rate of λ. Each message contains an average number of $\bar{h}$ packets. One packet can be served within one slot. Each station has infinite buffering capacity. The station transmits in average $\bar{v}$ packets before it gives up the reserved slot. In Table 1, the used variables and parameters are summarized.

A. Analytical Description

The analytical model for performance estimation of UTRA TDD ad hoc mode is based on the model derived for R-ALOHA with constant throughput assumption [17]. This model has been selected because it decouples the basic analysis of the R-ALOHA protocol from the specific details of the contention protocol. In the analytical performance evaluation, it is assumed

Table 1. Simulation parameters.

Symbol	Value	Description
N	14	Number of slots in frame
T	10 ms	Frame duration
M		Number of stations
n_{SF}		Number of frames per super-frame
λ		Arrival rate of messages at each station
$\bar{h}$		Average number of packets in message
$\bar{v}$		Average duration of busy period

that the actual data transmission happens only in the N_d remaining slots not used for the CSBC. N_d depends on the number of active stations, M, each reserving one CSBC in every super-frame, and the slots in one frame, N,

$$N_d = N - M/n_{\text{SF}}.$$

With the average delay, $\overline{d_A}$, for a successful transmission of a packet in a non-reserved slot, the average message delay for the steady state can be determined for the proposed access scheme with the following formula [17]

$$d = \frac{\bar{x}_0}{1-\lambda(\bar{x}-\bar{x}_0)} + \frac{\lambda\left(\overline{x_0^2}-\overline{x^2}\right)}{2\left[1-\lambda\left(\bar{x}-\bar{x}_0\right)\right]} + \frac{\lambda\overline{x^2}}{2\left[1-\lambda\bar{x}\right]}. \quad (10)$$

The mean service time of customers who initiate busy periods is

$$\bar{x}_0 = \overline{d_A} + (\bar{h}-1)T, \quad (11)$$

the mean service time of customers who arrive to find the queue busy is

$$\bar{x} = \bar{h}T, \quad (12)$$

and the respective second moments are

$$\begin{aligned} \overline{x_0^2} &= \overline{d_A^2} + 2\overline{d_A}(\bar{h}-1)N_d + \left(\overline{h^2}-2\bar{h}+1\right)N_d^2 \\ \overline{x^2} &= \overline{h^2}N_d^2. \end{aligned} \quad (13)$$

This result has been derived under the assumption that each user queue can be considered as a generalized M|G|1 queue in which the first customer of each busy period receives exceptional service. Because of the different access method, the derivation of the access delay, $\overline{d_A}$, and the second moment, $\overline{d_A^2}$, differ from that of pure R-ALOHA, and are given by [8]

$$\overline{d_A} = \bar{T}_{A,\text{first}} + n_A T_{A,\text{retry}} + \bar{T}_{A,\text{trans}}, \quad (14)$$

with the average waiting time, $\bar{T}_{A,\text{first}}$, until the first reservation attempt that is given by

$$\bar{T}_{A,\text{first}} = 0.5 n_{\text{SF}} T, \quad (15)$$

and the waiting time, $T_{A,\text{retry}}$, between any subsequent reservation attempts that is given by

$$T_{A,\text{retry}} = n_{\text{SF}} T. \quad (16)$$

For the estimation of $\bar{T}_{A,\text{trans}} = 1/2T$ we assume that the available slots are uniformly distributed over one frame resulting in an upper bound for the delay. The total number of reservation attempts to transmit one packet, n_A, can be derived under the assumption that a successful access attempt is only possible if at least one time slot is available in the frame following the slot of the CSBC. The probability that all slots are occupied is given by $P_{N_d} = U^{N_d}$, with U denoting the throughput of the system. Since the system is assumed to be in equilibrium, the channel throughput rate must be equal the channel input rate, and thus

$$U = M\lambda\bar{h}T/N_d.$$

With the probability for a successful transmission $P_d = 1 - P_{N_d}$, the first and second moment of the access delay, $\overline{d_A}$ and $\overline{d_A^2}$, can now be derived:

$$\overline{d_A} = \frac{T}{2} + \bar{T}_{A,\text{first}} + \frac{(1-P_d)}{P_d} T_{A,\text{retry}}, \quad (17)$$

and

$$\begin{aligned} \overline{d_A^2} = &\left(\frac{1}{3} + \frac{n_{\text{SF}}}{2} + \frac{n_{\text{SF}}^2}{3}\right)T^2 + \frac{(1-P_d)(2-P_d)}{P_d^2} T_{A,\text{retry}}^2 \\ &+ (1+n_{\text{SF}})\frac{1-P_d}{P_d} T T_{A,\text{retry}}. \end{aligned} \quad (18)$$

With these formulas, the average message delay for the proposed protocols can be determined. For a mathematically tractable exact analysis of the proposed protocol, it has been assumed that the CSBC is used for inband-signaling purposes only. In contrast to R-ALOHA, the inband-signaling on the CSBC is used to reserve resources without collisions. This is considered in (17) by the average initial access delay, which incorporates the waiting time until a slot is available to be reserved in temporary situations of high traffic load. By means of this access mechanism, there is no need for an adaptive control algorithm for contention (a back-off parameter or load dependent access probabilities) like in R-ALOHA. At the same time, this scheme allows to explore the free slots in an efficient way. For fairness reasons, it is foreseen that a station is forced to release a slot after a pre-defined duration, which is assumed to be ten super-frames, if all slots in a frame are reserved. This results in a trade-off between reservation overhead and delay. Alternatively, a station with low-priority traffic can be requested to release a slot by means of a respective message sent in the CSBC as described in [18].

B. Event-Driven Simulations

In the following, some basic performance measures for a fully meshed, static network without channel errors are derived by means of event-driven simulations [19]. It incorporates the protocols proposed for the air-interface and takes into account the different protocol states a station passes through as well as the reservation status of the slots in a frame.

B.1 Delay Performance

In Fig. 11, the curve on the left indicates the mean delay for the case that the CSBC is used for signaling only. If the net-

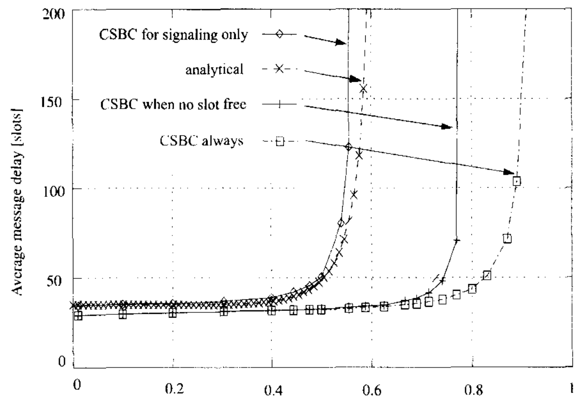

Fig. 11. Comparison of analytical and simulated results and results for different utilization of the CSBC ($N = 20$).

work is highly loaded and no slot is free that can be reserved by means of inband-signaling, it is beneficial if the capacity of the CSBC is used to transmit the message instead. This is indicated by the middle curve in Fig. 11. With this modification, the achievable throughput for 20 stations and a mean delay of 50 slots can be increased from approximately 50% to 75%. The throughput for a delay of 50 slots, which corresponds to less than 40 ms, can be further increased if the slots reserved for the CSBC are used whenever packets have to be transmitted. The achievable throughput for acceptable delays becomes approximately 85% and indicates an efficient operation of the proposed protocol. The difference to 100% can be explained by the overhead that is still needed for the inband-signaling on the CSBC (no user packet can be transmitted on the CSBC when an inband-signaling packet is transmitted to reserve a slot). In addition, a small amount of unused slots reserved for the CSBC when no message is to be transferred by the respective station will exist.

For a given delay requirement the throughput for the different modes of operation can be derived from Fig. 11, too. Reasonable delay values can be realized up to a throughput of 85% when the CSBC is used for packet transfer. In Fig. 11 the maximum achievable throughput increases from 58% by 20% up to 78% when the CSBC is used only when no slot is available and another 10% if the CSBC is always used when data have to be transmitted. The maximum throughput of approximately 90% corresponds to the available data rate of 100% minus the capacity needed for the fixed reserved slot in every frame for high priority services, which accounts for $13/14 \cdot 100\%$ of the total capacity.

The throughput will reach a constant and stable value, which is determined by the number of slots that can be used for data transmission only, since reserved slots are recognized and no collisions will occur.

B.2 Prioritization

So far, all stations have been assumed to use the same protocol parameters. However, FleetNet services will be distinguished by their QoS parameters. For example, services for cooperative driver assistance and inter-active games will require lower delays than services for marketing along the road. To fulfill this

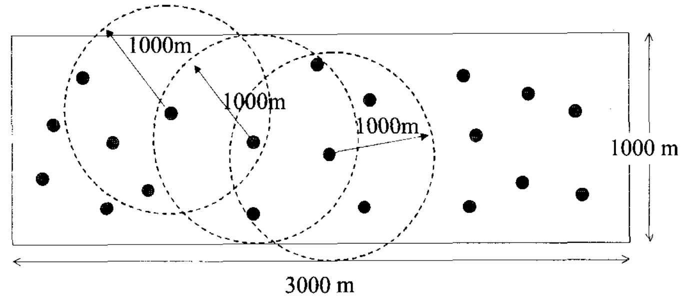

Fig. 12. Hidden station Scenario with uniformly distributed nodes ($N = 20$).

requirement of prioritization, different parameters for the period of the CSBC have been proposed in [19].

The period T_R of the CSBC is determined by the number of time units in frames for one reserved slot and defines the average delay. A period of $T_R = 8$ frames is equivalent to one CSBC every 8th frame, or a superframe length of $n_{SF} = 8$. As the period increases, the mean message delay increases approx. by the amount of the time that is additionally needed for the signaling on the CSBC. E.g., in [19] it has been shown that the mean delay for $T_R = 2$ is approx. 21 slots, whereas the mean delay for $T_R = 8$ becomes 63 slots. In summary, with increasing capacity for the CSBC, that is an increase of number of slots per time reserved for the CSBC, lower delays can be guaranteed.

It has to be noted that an increase of the number of packets per message has considerable impact on the delay as long as one slot is reserved for a busy period only. The delay for the proposed protocol increases by approximately one frame for each additional packet of a message assuming that only one packet can be served within one slot. Thus, we developed extensions that allow to allocate more than one of the non-reserved slots, if larger bulks of data are to be transmitted [20]. With these extensions, we comply with the expected wide range of traffic classes that FleetNet has to provide with different delay requirements from periodic data with small bandwidth requirements to user communication with high data rates and less stringent delay bounds [6]. It is therefore of high importance to provide a framework for services with different QoS requirements in parallel.

C. Impact of Hidden Stations

In the case of a fully meshed network each node is in communication range of each other node and will overhear and respect neighbor nodes' reservations. In the case of hidden stations, not all nodes may receive all reservations and the slot usage status of the system is not any longer unique in each node. Reservation conflicts (i.e., two nodes reserve the same slot for transmission) can occur, which may lead to packet collisions. A partly-meshed scenario comprising hidden stations is shown in Fig. 12. The simulation area is set to 3000 m × 1000 m, where all twenty stations are distributed uniformly over the area. Each station has about four direct neighbors and about five stations are hidden.

Compared to a fully-meshed scenario, where every station can communicate with an arbitrary station, the achievable throughput in the system could be increased due to frequency-

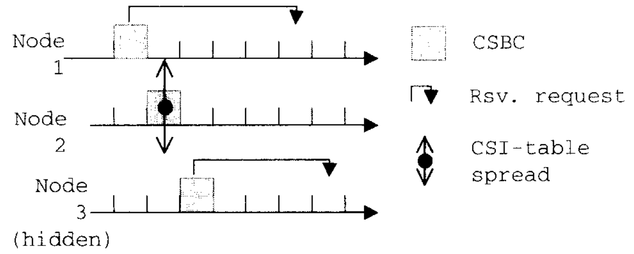

Fig. 13. Spreading of CSI to prevent from collisions.

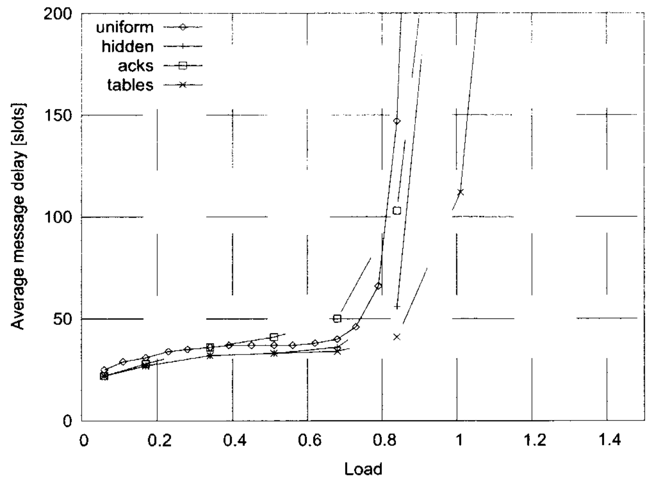

Fig. 14. Average message delay (N = 20).

reuse. However, due to hidden stations, reservation conflicts will occur and, therefore, packet collisions, which will reduce the maximum achievable throughput. In the basic scenario, called *hidden* in the sequel, if the receiver detects packet collisions, it indicates this to the sender by setting a collision flag inside its message in the next CSBC. If the sender detects this flag, it cancels its reservations and starts a new reservation procedure. To resolve and avoid packet collisions, two mechanisms are used [21]: In the first approach, called *acks* in the following, the receiver will explicitly acknowledge reservations, i.e., if a reservation is received and packets can be correctly decoded by the receiver, it sends an acknowledgement (ACK) back to the reserving node. If the receiver detects a collision, it will send a negative acknowledgement (NACK). While the CSBC will be used to send these (N)ACK packets, a maximum of 4 collisions per reserved resource may occur, depending on the position of the CSBC. In the second approach, called *tables* in the sequel, each node will add information on used resources in terms of a CSI to each packet transmitted with the CSBC. This CSI can contain full information on the state of all channels (e.g., channel free/channel busy/interference detected), but this will lead to a big overhead, since the state of all 56 slots inside one superframe has to be signaled. Investigations in [15] showed, that it is sufficient (and more efficient) if each node spreads information only on slots used for receiving to all of its neighbors. By collecting the CSI from all neighbors, a node gets an actual knowledge on the reservation status of the available resources in its vicinity.

In the example depicted in Fig. 13, node 2 spreads its CSI containing information which slots it is intended to use for reception in the future: Here, the CSI includes the slot reserved by node 1. This would prevent node 3 from reserving the same slot. Additionally, because the CSI is received by node 1, this also acts as a reservation acknowledgement. This mechanism is slightly comparable to the RTS/CTS handshake mechanism of the IEEE 802.11 MAC: The resource reservation message inside the CSBC acts like an RTS and the reception indication via the CSI acts like a CTS message. However, using the CSI, more than one reservation can be acknowledged by just one CSI message, reducing overhead in comparison to a dedicated CTS sent by each intended receiver to every corresponding transmitter. Fig. 14 shows the average message delay for a population of 20 nodes. The load-axis is normalized to the max. achievable transmission rate of the air-interface.

Each station has a maximum amount of nine slots available for data transmission: One CSBC and up to eight additional resources that can be reserved on demand. The amount of actually reserved resources depends on the buffer occupancy of each station. The first slot is reserved if more than two packets are stored. The second slot is reserved, if more than five packets are stored, because with one reserved slot five packets can be transmitted per superframe (one packet per frame and one packet inside the CSBC). The third slot is reserved if more than ten packets are stored, and so on. The maximum achievable load is approx. 85% in the *uniform* scenario, where all stations are in communication range, since ≈7% of the capacity is used for high priority services and the rest are either unused CSBCs or used CSBCs for signaling purposes.

In the *hidden* scenario, the delay shows a slower increase, and the maximum achievable load is increased to approx. 90%. Using *tables* the max. supported load increases to 105%. If *acks* are used, approx. 90% of the load is reached.

This increased max. achievable load and lower delay for low to medium offered load, compared to the *uniform* approach, is caused by the increased simulation area and exploitation of frequency re-use, but the high collision rate due to hidden stations avoids a further increase. The collisions even limit the load in the *hidden* scenario approx. to the same value as for the *uniform* scenario. The limiting factor is the collision rate caused by reservation conflicts. No collisions occur in the *uniform* scenario since reservation requests are correctly received and are accepted by all stations. The very high collision rate in the *hidden* scenario can be reduced by more than a half in the cases *acks* and even more when *CSI tables* are used.

If an (N)ACK packet is transmitted, no data packets can be sent inside the CSBC. In contrast, CSI tables can be transmitted piggybacked, i.e., the CSBC can be used to transmit data packets and the overhead is lower than for the ack approach. This leads to a better delay, resp. throughput performance using CSI tables, (cf., Fig. 14), because more resources are available for data transmission. The CSI approach leads to the lowest collision rate, because a sender can forecast free resources at the receiver—even if a sender is hidden—because all nodes broadcast their full reception status once every superframe. This is even more important if resources are scarce. ACK packages are only sent once, and NACK packets only if a collision occurred.

D. Impact of Mobility

So far a simplified scenario has been considered, because no mobility and topology aspects have been taken into account. This is, however, a crucial aspect in mobile ad hoc networks and will be investigated in more detail in the next sections.

D.1 Connection Duration

A fundamental question that stems from the dynamics of topological changes and hence the useful period of time when a reserved channel can be used. The starting point is a worst-case scenario in which one connection is considered between two vehicles that drive on different lanes in opposite direction and with maximum velocity of $v_{\max} = 250$ km/h. Furthermore, it is assumed a decoding range of $R_{\text{dec}} = 1$ km. Under these conditions the two vehicles will have a connection duration of

$$t_{\text{con}} = \frac{2R_{\text{dec}}}{2v_{\max}} = \frac{2 \cdot 1 \text{ km}}{2 \cdot 250 \text{ km/h}} = 14.4 \text{ sec}, \quad (19)$$

for communication. This time corresponds to a duration of 1440 frames where a slot can be reserved for data exchange. From this example, it can be seen that even for extreme conditions reservations over several frames can be supported. In the next step, a realistic distribution of vehicles on the highway is assumed. According to classical vehicular traffic theory, time gaps between vehicles are assumed to be negative-exponentially distributed and the velocity is generally assumed to be normal distributed [22]. The connection duration for oncoming traffic can be derived from the following probability distribution function (PDF) [23]:

$$p_t(t) = \frac{4R_{\text{dec}}}{\sigma_{\Delta v}\sqrt{2\pi}} \cdot \frac{1}{t^2} \cdot e^{-\frac{\left(\frac{2R_{\text{dec}}}{t} - \mu_{\Delta v}\right)^2}{2\sigma_{\Delta v}^2}} \quad \text{for } t \geq 0, \quad (20)$$

whereby $\mu_{\Delta v}$ and $\sigma_{\Delta v}^2$ are the average value and variance of the velocity difference, and $\sigma_{\Delta v} = 0.3\mu_{\Delta v}$. In Fig. 15, the resulting distribution functions of the connection duration t_{con} for different mean velocities v_m are shown.

In case of $R_{\text{dec}} = 1$ km and oncoming traffic, typical durations exceed 141 sec for $v_m = 30$ km/h and 28 sec for $v_m = 150$ km/h in 95% of the cases. These values are equivalent to 14100 and 2800 frames, respectively.

From this discussion, it becomes obvious that reservation of slots for user data transmission as well as slots for CSBC over a relatively long time period will be useful for an efficient operation and low delays as indicated by the results in the previous sections.

However, this consideration of the topology dynamics gives only a first impression of the suitability of the proposed protocols. In [24], some simulation results based on movement data produced by the traffic simulation tool DYNEMO as well as on data retrieved from Daimler-Chrysler simulations were presented. These results showed that from the analytical investigations a good and realistic impression on the traffic dynamic can be derived.

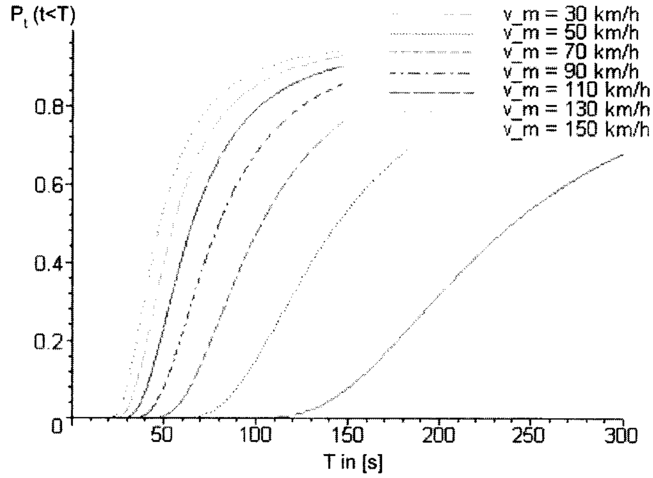

Fig. 15. PDF of communication duration t_{con}.

VII. SUMMARY

In this paper, a new air-interface for self-organization, especially suited for inter-vehicle communication, has been presented. It is based upon the UTRA/TDD standard and supports highly dynamic topologies. Simulations have shown that it outperforms the standard IEEE 802.11 with respect to velocities and communication ranges.

To adapt the standard to the requirements of FleetNet, the Internet on the Road, a novel synchronization scheme has been introduced. This decentralized scheme achieves a locally common slot timing of all nodes within their respective range of influence.

Changes on the data link control layer comprise an innovative concept for a reservation-based single-transmitter concept for the medium access control, and a distributed radio resources management scheme based on the dissemination of receiver-based status information. Analytical as well as event-driven simulations indicate high values for the throughput and almost constant delays until network saturation.

Additionally, the routing algorithm proposed for FleetNet has been outlined, but is not explained in detail because of space limitations.

It is expected that this new approach for an air-interface is a promising candidate not only for inter-vehicle communication, but also for other self-organizing wireless networks that need to support high communication ranges and high mobility.

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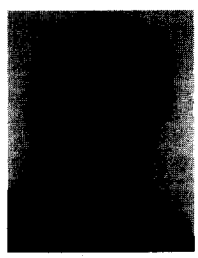

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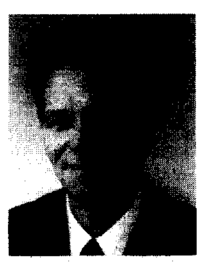

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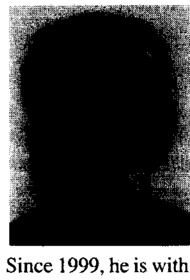

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