A Frequency Agile Air-Interface for Inter-Vehicle Communication

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***Abstract*-One of the most promising deployment areas of mobile ad hoc networks are inter-vehicle communication and road telematics. The diverse spectrum of applications requires the full range from low to high data rates. To provide broadband services with moderate terminal complexity and explore the available radio spectrum at the same time, frequency division multiple access (FDMA) should be introduced. In the FleetNet project an appropriate air-interface based on UMTS Terrestrial Radio Access Time Division Duplex (UTRA TDD) is under development. One component is the novel FDMA concept, which is introduced in this paper, and which enters an evolutionary path towards higher data rates. The concept takes into account the complexity of the hardware, the distributed character of self-organizing networks, and the efficient exploration of the scarce frequency spectrum. Simulation results for the new decentralized FDMA scheme show high and efficient utilization of available resources.**

Keywords

Wireless ad hoc network, UTRA TDD, low chip rate, FDMA, medium access control, inter-vehicle communication, FleetNet.

1. INTRODUCTION

Today the Internet plays a fundamental role for the communication between people and the data exchange in daily life. At the same time communication into and between vehicles, also known as intelligent transportation systems (ITS), has attracted major attention during the last few years [1]. FleetNet [2] brings together these two emerging technologies by building up a mobile Internet for communication with and between vehicles. Thus, FleetNet extends the deployment of the Internet towards a new application area, which is expected to be one of the most attractive for wireless ad hoc networking. This novel mobile ad hoc network serves for voice and data communication, road traffic telematics and for entertainment purposes, and it can be expected that such systems will become standard equipment in future vehicles.

As a basis for the air-interface, UTRA TDD has been chosen for providing the entire range of FleetNet applications. Since UTRA TDD is based on an infrastructure, a new UTRA TDD ad hoc mode was introduced for FleetNet [3], [4]. However, for a smooth evolution towards higher data rates with minor changes of the existing air-interface the exploration of the existing frequency bands should be aimed at. The most obvious approach is to explore more frequency channels by means of frequency division multiple access (FDMA).

In existing cellular mobile systems the assignment of different frequencies to cells is controlled by the respective base station. Depending on the number of transceivers a base station is equipped with, several frequencies can be explored by means of dynamic channel assignment. In a system with decentral organization, e.g. an ad hoc network, there is no central instance that can take over the frequency channel allocation. For self-organizing systems without an infrastructure spread-spectrum (SS) techniques are applied to share a broad spectrum by several users, e.g. frequency-hopping in Bluetooth or direct-sequence SS in wireless LAN systems like IEEE 802.11 [6]. However, SS schemes in these systems are used to combat fading and interference, e.g. microwave ovens, and to separate individual user groups and hence, the max. data rate between individual users within a group is restricted to one spreading sequence. This holds for HIPERLAN/2, too, which uses different frequency channels to separate user groups [6]. The communication within each user group is restricted to one frequency that is chosen by means of the so-called dynamic frequency selection procedure. Thus, the original motivation to increase the data rate is not fulfilled by the schemes incorporated in IEEE 802.11, Bluetooth, or HIPERLAN/2. The approach that comes closest to a solution is incorporated in the DECT (Digital Enhanced Cordless Telephone) system [6]. However, in the basic mode a base station controls the access and in the relaying mode broadcast transmission and peer-to-peer communication is not adequately supported for an ad hoc operation.

In this paper a concept for a decentralized Frequency Division Multiple Access (dFDMA) scheme in FleetNet is introduced. It allows to efficiently explore all available frequency channels with one transceiver only, and thus serves the requirement of low hardware complexity and a smooth evolution towards higher data rates. The paper is organized as follows. In Section 2 the requirements for FDMA in ad hoc networks are discussed and a new solution for decentralized FDMA (dFDMA) is described.

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In Section 3 it is explained how this scheme can be used in FleetNet, and in the following Section 4 the performance of dFDMA is evaluated by means of event-driven simulations. It is demonstrated by the results that the novel concept serves to efficiently explore the available frequency channels and allows for higher data rates and low delays. In Section 5 a conclusion and an outlook to ongoing activities is presented.

2. FDMA IN AD HOC NETWORKS

With new and more sophisticated applications the communication systems have to provide higher data rates. At the same time the user seeks for cheap equipment which restricts the complexity of the hardware to a minimum and hence the supported receive bandwidth of an individual station. Moreover, developing costs and standardization efforts motivate for an evolutionary approach that re-uses air-interface technologies. In addition, frequency planning, spectrum allocation including channelization is a time-consuming process. As a logical consequence, it is proposed in this paper to explore available frequency bands by means of FDMA with modifications of existing air-interface concepts. Different to existing approaches used in cellular networks, the new approach should be applied to self-organizing networks with decentralized organization, like ad hoc networks or peer-to-peer networks, where everybody should be able to communicate with each other. With the distributed assignment of different frequency channels in such networks the following requirements arise, especially if only one transceiver is desired.

Broadcast is the most important service to operate a wireless system. If stations are tuned to different frequencies a broadcast that is relevant for all stations should be sent on all frequencies. This might increase latency, reduce reliability, and increase the amount of transmitted data. This becomes even more critical for safety-related messages.

There is a requirement to reach/access any arbitrary station for information exchange. If stations change their frequency the resources on which a station can be reached should be made available to the other stations. This requires considerable management efforts. Moreover, for dynamic allocation of resources different carrier frequencies and respective slots have to be measured and the status (reserved, free, collision, etc.) has to be monitored. At the same time blind slots make this task even harder. Blind slots occur when a station transmits / receives on one frequency, the other frequencies cannot be measured or used at the same time with affordable hardware complexity, e.g. with one transceiver only. Also, to explore the different frequencies time is needed for frequency switching. In addition, if more than one carrier frequency is used for transmission but only one frequency can be decoded at one time instance, receptions of transmissions as well as resource reservations without conflicts can not be assured. E.g., the setup of a new connection might fail if the target station is tuned to another frequency.

Though this section covers not all challenges, even from these requirements it becomes obvious that a further degree of freedom makes the organization and a solution much more complicated.

2.1 DECENTRALIZED FDMA

The decentralized FDMA (dFDMA) concept foresees to logically subdivide time into two different phases. During the first phase, the so-called *exchange phase (EX-phase)*, a station listens and transmits on a predefined frequency, the coordination frequency, f_{coord}. On this frequency a station can announce reservation requests, send out beacons for the network organization, broadcast relevant or time-critical information to neighbors, exchange signaling information to run the protocol and manage the radio resources in a decentralized but controlled manner, etc.. During the second phase, which will be referred to in the sequel as *arbitrary transmission phase (AT-phase)*, the station is no more restricted to one carrier frequency. The station is rather allowed to arbitrarily explore all available frequencies, f_i. During the AT-phase the station only has to take into account its communication relationships, and has to measure and test the available resource units that it is currently using and that it might use at a later time for transmission or reception.

Since all frequencies in parallel to the coordination frequency cannot be used by stations that have only one transceiver and that are in the EX-phase, different *frequency patterns* are introduced, which define concurrent exchange and AT-phases. The phases of the frequency patterns are equidistant in time. An example for three frequency patterns is shown in Figure 1.

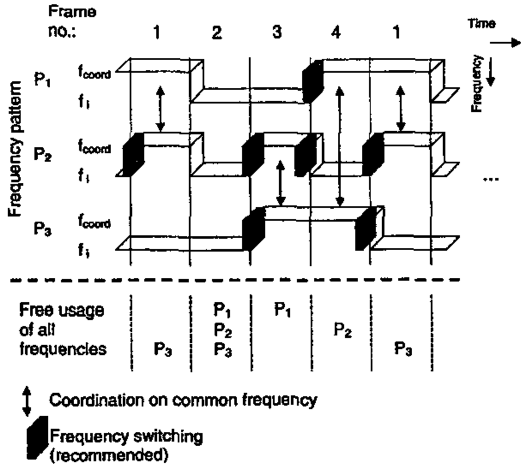

Figure 1. Selection of frequencies in dFDMA, based on frequency patterns

Each frequency pattern will be repeated after four phases. For example, a station using frequency pattern one, P_1, will start with the EX-phase, i.e. operation on the coordination frequency, switches then for two consecutive phases to one or more arbitrary frequencies (AT-phase), and afterwards switches back to the coordination frequency, before it starts from the beginning. Advantageously, one phase corresponds to one frame if the dFDMA concept is applied to a framed system. The stations belonging to other patterns, P_2 and P_3, switch to the coordination frequency at different times, e.g., in case of P_2 in the first and third frame, and for P_3 in the third and fourth frame. Nevertheless, there are common times where stations belonging to two different patterns are jointly using the coordination frequency, e.g. frame 1 for the patterns P_1 and P_2, see Figure 1. It is therefore guaranteed that two pattern, P_i and P_j, always have a common phase within four sequential phases, respectively frames. This guarantees a delay of four phases for the exchange of any information between stations within the decoding range (and as long as no channel errors occur).

2.1.1 Optimal Frequency Patterns

A station can join one of the three possible patterns. The number of three patterns is the minimum number that supports the permanent exploration of all frequencies with one transceiver only. Moreover, it is the maximum number of possible patterns with a period of four phases and no more than two EX-phases. There exist 2^4 possible combinations of EX- and AT-phases. Since at least two EX-phases are needed to communicate with stations of the two other patterns the number is reduced by 5 (only AT-phases and all possible combinations with one EX-phase only). Further 5 examples are excluded if no more than two EX-phases are allowed to support a max. number of AT-phases for each pattern. Only half of the remaining 6 patterns will be possible, since the complementary patterns of the 3 patterns shown in Figure 1 will have disjunctive EX-phases which makes an information exchange between stations of these patterns impossible. Of course more patterns can be introduced with more EX- and AT-phases, e.g. four patterns with a minimum of three EX-phases, but they will increase the latency of common EX-phases, respectively the repetition interval, and is therefore left out of consideration.

Furthermore, the length of the EX-phase is the largest possible common duration for all patterns, which allows to explore all available resources (all frequencies) at every time. An extension of the EX-phase leads to overlapping EX-phases for all three patterns that in turn precludes the exploration of other frequencies. A reduction of the EX-phase is possible with the drawback of reduced time to exchange broadcast / multicast messages. Hence, it can be followed that the example of the three frequency patterns depicted in Figure 1 represents the optimal distribution of exchange and AT-phases.

2.1.2 Impact of Frequency Switching Time

Considering the frequency pattern as depicted in Figure 1, a station that has selected the pattern P_1 needs the last slot in frame 3 to switch to the coordination frequency in time, as far as we assume a frequency switching duration of one slot. The stations using P_2 and P_3 are also using the coordination frequency at that time. Hence, the other frequencies cannot be explored. To avoid this potential waste of capacity an exception rule for the EX-phase is applied for stations of pattern P_2. They are allowed to switch to any other frequency 2 slots before the 3rd frame ends. Hence, they start 2 slots earlier the AT-phase. With this modification that is applied to the other frequency pattern at the respective times, too, all slots at any frequency can be used if required, and all available resources will be explored. At the same time the EX-phases are shortened by two slots. The resulting recommended frequency switching times are shown in Figure 1.

2.1.3 Avoiding Reservation Conflicts

Reservations of new resources are performed during the EX-phases. Only stations of the respective frequency patterns are then aware of this reservation. If the reservation is restricted to the AT-phase this pattern is exclusively using and frequencies excluding the coordination frequency there will occur no conflict. However, if a reservation is done for the AT-phase that is common to all patterns (frame 2 in Figure 1) this might be different. E.g., a station belonging to pattern P_3 can make a reservation in frame 3 for the AT-phase in frame 2 of the next superframe. This reservation is not recognized by stations of pattern P_1. Hence, the same slot in frame 2 might be reserved during the EX-phase in frame 1 by a station of pattern P_1. To avoid this conflict one solution would be that stations of pattern P_3 will announce their reservation request for the common AT-phase in frame 2 twice (in both EX-phases). Alternatively, stations of pattern P_2 (P_1) will inform the station of the other pattern P_1 (P_2) about a potential reservation conflict, if a station of pattern P_3 has made a reservation during frame 3 (frame 4).

2.1.4 Advantages and Limitations

Due to the fact that one single transceiver is sufficient, the hardware complexity of the system remains low but still all frequency channels can be simultaneously used at all times by all stations within decoding range. This leads to an efficient exploration of the given resources. Another outstanding advantage is the support of power saving algorithms since a station only needs to decode slots on the known frequency during the EX-phase whereas during the AT-phase it might turn-off its receiver, respectively go into sleep-mode. This time can also be used for collecting measurement reports on other frequencies for later usage.

The proposed concept has – of course – also some limitations. The required frequency-switching needs time that is inherited by all FDMA approaches. With a second synthesizer the switching time can be reduced but this would be in contrast to the desired low hardware complexity. With appropriate and intelligent scheduling of switching times there is no loss in overall capacity, though the individual user capacity is reduced. The concept also leads to reduced flexibility and lower max. possible data rate, since the duration for the usage of all frequencies is limited to the AT-phase. At the same time the organization of the resources for transmission and reception becomes more complicated, since more resources are available and stations will not listen to all other stations within the decoding range all the time. However, this is comparable to cellular systems. Furthermore, the selection of an appropriate frequency pattern and joining the respective group has to be managed. Finally, the overhead needed for broadcast transmission increases because data has to be transmitted twice to reach all stations in decoding range. Estimations of the impact of the mentioned disadvantages on the performance will be given in Section 4.

3. dFDMA IN FLEETNET

In this section it is explained how the dFDMA concept can be applied to the air-interface of FleetNet, which is based upon UTRA TDD. In Europe there exists an unlicensed frequency band at 2010 - 2020 MHz for UTRA TDD. Considering the bandwidth of UTRA TDD low-chip rate (LCR) of 1,6 MHz, and further assuming a 5 MHz band reserved exclusively for IVC, three frequency channels can be made available.

3.1 FleetNet Air-Interface

UTRA TDD LCR has a radio frame of 10 ms duration and is sub-divided in two sub-frames with 7 time slots each. Following the first time slot an additional special time slot for synchronization issues is inserted, which has a duration of 275 μs, see Figure 2.

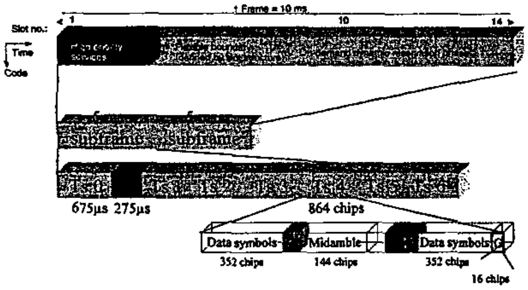

Figure 2. UTRA TDD ad hoc frame structure

Each of the following time slots have the same length and structure as the first time slot and comprise two data parts that are separated by a midamble and a guard period (G).

In contrast to the cellular mode of UTRA TDD, the ad hoc mode requires a decentralized synchronization scheme. Since there is no central instance in the ad hoc mode, it is assumed that coarse time synchronization for frame and slot boundaries is achieved by use of the Global Positioning System (GPS). Fine synchronization is almost identical to the mechanisms used within the cellular mode of UTRA TDD, which is based on the midamble transmitted within each time slot. However, to increase performance it is proposed in [5] to introduce a two-stage frequency synchronization. With the proposed synchronization mechanism it is assumed that a one-shot synchronization can be achieved in the UTRA TDD ad hoc mode.

For the ad hoc mode of UTRA TDD the same spreading codes as for the cellular mode (spreading factor, SF: 1, 2, 4, 8, 16) are used, which enables the usage of up to 16 codes in parallel in one slot. Hence, transmit capacity is provided by a combination of a) codes, b) slots, and c) frequency. To preclude the power-impairment problem[1] that is associated to a CDMA component[2] 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) can be simultaneously reached by one station. The approach, therefore, still exploits the advantage of fine granularity of capacity offered by the CDMA component over a pure TDMA system.

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. For that purpose, a certain part of the capacity in terms of slots in a frame is constantly reserved, see Figure 2. The minimum number of these high priority slots, N_{high}, is a system parameter and assumed to be $N_{high} = 1$ in the following. The remaining part (*on-demand dynamic reservation phase*) can be dynamically assigned and temporarily reserved by different stations for several services with lower priority, Whereas the reserved capacity for high priority services can be accessed by means of reservation ALOHA (R-ALOHA), the remaining part is utilized by means of a novel inband-signaling approach. To gain access to the radio medium it is proposed to permanently reserve a small amount of transmit capacity, even if no user data packets are to be transmitted. This mode results in a circuit-switched broadcast channel (CSBC) that is primarily used for signaling purposes. For the initial reservation attempt of the CSBC, reservation ALOHA (R-ALOHA) is used [3]. When a user data packet has to be transmitted and the CSBC does not provide enough capacity, it is used to transmit a reservation request and hence, to reserve capacity in terms of a periodic time slot by means of inband-signaling. This is the common access procedure for slots in the on-demand dynamic reservation phase of the frame. All stations in the vicinity of the requesting station recognize this request and will not attempt to reserve the same slot. The advantage is that this kind of reservation results in controllable competition without collisions and that the reservation of further

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[1] The phenomena 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.

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

capacity can be performed within a limited time until the CSBC is available. The reserved capacity for user data packet transfer is only used and reserved by means of piggyback signaling (R-ALOHA with end-of-use flag) as long as packets have to be transmitted and is released after successful transmission.

3.2 Frequency Agile Transmission in FleetNet

Introducing the dFDMA approach in FleetNet each active station has two CSBCs reserved during the EX-phases. Stations of pattern P_1 have one in sub-frame 1 and 4 each, stations of P_2 in sub-frame 1 and 3, and stations of P_3 in sub-frame 3 and 4. Exemplary selecting a station S_i using pattern P_2 it will reserve one CSBC in sub-frame 1, e.g. slot 2, and slot 3 in sub-frame 3 as shown in Figure 3.

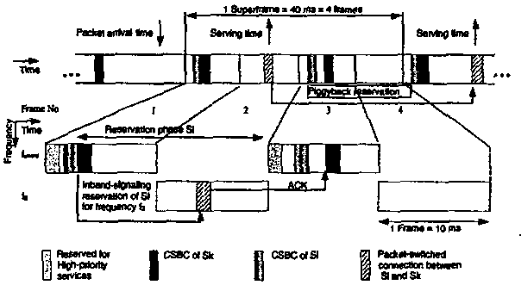

Figure 3. Example for capacity reservation by means of CSBC

In each frame on the coordination frequency, f_{coord}, one slot is reserved for high-priority services.

3.2.1 *Connection Setup*

Station S_i will use the CSBC slot in frame 1 to transmit a resource reservation request for any connection to a station using the same pattern P_2 or pattern P_1. E.g., if S_i wants to reserve a slot on frequency f_2 to communicate with station S_k in frame 2 in slot 6, it will transmit a respective reservation request message. This message will contain the slot number, sl_6, the frame number, sf_2, and the frequency, f_2. The receiver, S_k, will switch in the next frame for slot 6 on frequency f_2. Different to [4] a slot is not reserved in every directly succeeding frame but one superframe equals four frames later, since station S_i has to switch to the coordination frequency in frame 1 and 3. Furthermore, if station S_k belongs to a different frequency pattern group P_1, it will not be able to receive a packet on frequency f_2 in frame 4. To avoid such reservation conflicts it is suggested that with each unique station ID also the frequency pattern that the station is using will be stored, e.g. in the neighborhood table. Three frequency patterns can be encoded with 2 bits. The fourth status is reserved for a station that solely operates on the coordination frequency and does not support the operation on other frequencies. This allows a smooth integration of the new concept in already existing systems.

However, if a reservation conflict has occurred this will be recognized in the next CSBC of the communication partner since the status (acknowledgement, ACK, or negative ACK, NAK) of the slots that have been selected for reception in the preceding frames after the previous CSBC is signaled, see Figure 3. Here, station S_k has successfully received the packet in frame 2 and will acknowledge this packet in frame 3 on the coordination frequency.

4. PERFORMANCE RESULTS

In order to evaluate the performance of the proposed dFDMA concept an event-driven simulation environment based on the C++ class library CNCL[3] has been built up. It incorporates the protocols presented in this paper and takes into account the different protocol states a station passes through as well as the reservation status of the slots in a frame.

In the following Table 1 the simulation parameters are summarized.

Table 1: simulation parameters

T	10 ms	Frame duration
n_{sf}	4	Superframe length (frames/superframe)
N	14	Slots per frame
N_{high}	1	High priority slots per frame
M	18	Population
λ		Packet arrival rate
n_f	3	Number of available frequencies

A frame with duration of T = 10 ms comprising N = 14 slots is considered (N_{high} = 1 slot is permanently reserved for high priority services). The topology is a fully meshed network with a population of M = 18 stations. No velocity is assumed and no channel errors are considered. Simultaneous transmission of more than one station results in collisions. No capture-effect is taken into account. In this simplified model a slot is free of interference or reserved and then unserviceable for any other station since a fully meshed network is assumed. All stations have identical packet arrival statistic that follow a stationary Poisson process with rate λ. One packet can be served within one slot. Each station has infinite buffering capacity.

In the single-frequency approach (no dFDMA) one slot for the CSBC is provided for each station in every superframe, whereas a superframe contains n_{sf} = 4 frames. Opposed to this for the dFDMA approach two CSBC slots are reserved for each station in every superframe. Data packets can be served in CSBC slots. If this capacity is not sufficient, it is assumed that another slot can be reserved by means of an inband-signaling message, which is transmitted piggybacked with the user data packet. This additionally reserved slot is then used in every frame in the case no

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[3] CNCL: Communication Networks Class Library, available from http://www.comnets.rwth-aachen.de

dFDMA is applied, whereas the slot is used in every superframe in case dFDMA is used.

4.1 Frequency Pattern Assigment

For dFDMA the stations are uniformly distributed on the three frequency patterns. For the sum of 18 stations there are always 6 stations assigned to each individual frequency pattern. Each station is assigned one target destination, which is not changed during the simulation. Two different allocation schemes for the destinations exist:

- *diff*: Source and destination belong to different frequency-patterns (except on the common coordination frequency they only can communicate during frame 2, where they can explore all possible frequencies).
- *com*: Source and destination belong to one common, i.e. the same frequency-pattern.

Within the simulations all stations belong to the same allocation scheme, either *diff* or *com*.

The resulting mean delay as function of the load normalized to the max. possible capacity of one frequency channel is depicted in Figure 4.

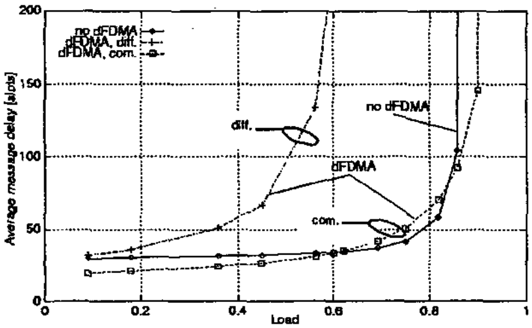

Figure 4. Mean delay for M=18 stations using dFDMA

Under low load the delay for dFDMA using different frequency patterns (*dFDMA/diff*) is comparable to the delay when not using dFDMA since the one CSBC slot every superframe is sufficient to serve the user data. For *dFDMA/diff* only one of the two CSBC slots a station has reserved can be explored for data exchange since different frequency patterns have only one common EX-phase comprising the CSBCs. In contrast to this stations using common frequency patterns for data transfer (*dFDMA/com*) utilize both CSBC and can considerably reduce the delay under low load conditions. In mean only half of the delay is needed for *dFDMA/com* since twice the capacity is provided, i.e. the mean delay is reduced approximately from half of a superframe to a quarter of a superframe. However, with increasing load the delay dramatically increases for dFDMA, especially for *dFDMA/diff*, since the additional capacity provided by one slot every superframe is far too small. For *dFDMA/com* the additional CSBC reduces this deficiency, but still, the delay considerably increases. However, compared to the single-frequency appliance it can be recognized that *dFDMA/com* can offer higher total throughput. This is the result of the other available frequencies that can be used to reserve always an additional slot for data transfer. Therefore, each station under saturation for *dFDMA/com* has two CSBCs and another slot every superframe for data transfer. This reduces to one CSBC and one additional slot for *dFDMA/diff*. When using no dFDMA all stations have to share the $n_{sF} * N = 52$ slots in a superframe for data transfer. From these slots further $M = 18$ slots have to be subtracted, which are reserved for the CSBC. Hence, each station has one CSBC and in mean another 34/18 slots in every superframe, which is less than for *dFDMA/com*.

4.2 Increasing Transmit Capacity

Nevertheless, such low utilization of three available frequencies in case of dFDMA is far below as been expected from three times the capacity of a single-frequency. The main reason for the low throughput for dFDMA is the limitation of reserved capacity to one slot only in every superframe besides the capacity provided by CSBCs. In the following it is therefore assumed that each station is allowed to reserve up to 10 slots on all frequencies to explore the available resources in an efficient way. The resulting delays are shown in Figure 5.

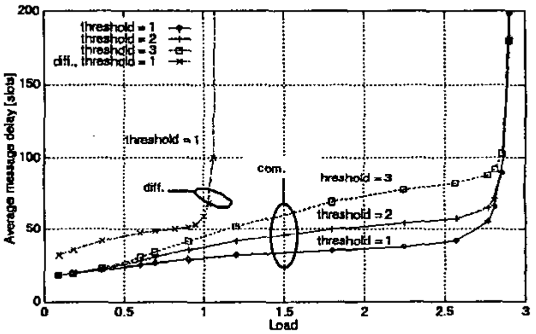

Figure 5. Mean delay for dFDMA utilizing up to 10 slots

To reserve another slot the number of packets in the queue is taken into account. If the number exceeds a given threshold multiplied by the number of already reserved slots another slot is reserved. The first slot is reserved when the CSBC slot is available and if more than two packets are in the queue. For a threshold = 3 the second and third slot is reserved when more than 3, respectively 6 packets are in the queue.

As indicated in Figure 5 the delay decreases with smaller thresholds, as expected, since more resources are reserved to emptying the queue. At this point it has to be mentioned that with smaller thresholds the signaling overhead for reservation requests increase. This overhead has not been considered so far, and it has been implicitly assumed that a reservation request can be signaled piggybacked with user data. A discussion of the effect of signaling overhead on the performance will follow below. It can be further recognized that with *dFDMA/com* and an adaptive and variable number of reserved slots the throughput can be increased close to the theoretical max. of three times the value a single-frequency provides. The throughput decreases to approx. 120% only in case of *dFDMA/diff*, since only one common frame, frame 2 in Figure 1, for data exchange exists for communication partners assigned to different frequency patterns. Moreover, the slots on the coordination frequency are all reserved for the CSBCs and only 50% of these slots can be used for data transfer because of different frequency patterns of the corresponding receiver. In typical scenarios a throughput between these extreme values can be expected, whereas the allocation strategy allows to shift the throughput towards the max. possible value. For example, communication between stations using the same frequency pattern should be directed to frames excluding frame 2, which is primarily used for data exchange of stations assigned to different frequency patterns.

4.2.1 Impact of Signaling Overhead

Two different approaches to increase the capacity are investigated: 1. The *idealized* approach, where no additional signaling-overhead exists, and 2. the more *realistic* approach, in which a reservation request for further capacity requires one slot. In the idealized case, which has been presented in the previous section, it is assumed that this reservation message is transmitted piggybacked with the user data packet. In this case the reservation of further slots does not generate any signaling overhead. Moreover, a new slot can be reserved piggybacked with a data packet that is transmitted on an arbitrary frequency at any position in the frame. Though this piggyback reservation will be received by the destination and can be used to increase the capacity on an existing link, it might not be overheard by other stations and, hence, is a source for a potential reservation conflict. In the more realistic approach it is assumed that only the CSBC can be used to increase transmission capacity and at the same time no user data packet can be served.

The additionally reserved slots are used in every superframe as long as packets are in the queue. After all packets have been transmitted, all temporarily reserved slots are released with one single message transmitted with the last user data packet.

The resulting mean delay as function of the load normalized to the max. possible capacity of one frequency channel is depicted in Figure 6. All stations use a common frequency-pattern (*com*).

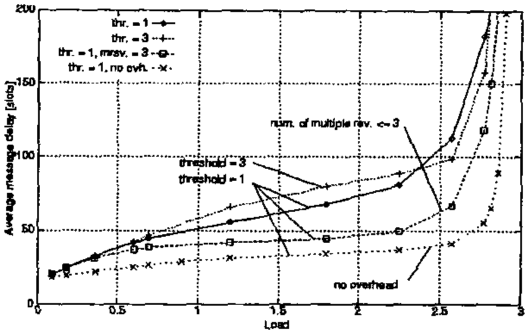

Figure 6. Mean delay for dFDMA with and without considering signaling overhead

The curves with the highest delays result from simulations taking into account the signaling overhead. For a load of 200% the delay is approx. 70 and 80 slots for a threshold = 1, respectively 3, which corresponds to 50, resp. 57 ms delay. Compared to the delay of 30 slots for the idealized approach without overhead (no overhead), the impact of signaling is considerable. Because of the signaling messages, which are only allowed to be transmitted on the CSBC, the available capacity for signaling requests is reduced in contrast to the idealized approach where the CSBC and all reserved slots for a connection can be utilized. Hence, it takes much more time in the realistic approach to reserve new slots on demand. In addition, the available transmit capacity is reduced by the signaling capacity needed to transfer the requests. This becomes more problematic for higher loads close to saturation, e.g., above 240% the delay for the low threshold of 1 results in higher delays than for a threshold of 3. However, for lower loads there is enough capacity left for signaling purposes and a lower threshold equals 1 results in better performance. Still, the time to reserve new slots is comparably large.

4.2.2 Multiple-Slot-Reservation

To increase the transmission capacity faster an extension to the common approach is introduced. Instead of reserving only one slot with a reservation request it is now allowed to reserve up to three slots simultaneously, if the number of packets in the queue indicate such needs. With this multiple-slot-reservation (MRSV) it becomes possible to reserve 3 additional slots on each CSBC, which makes up to 6 slots every superframe, if the destination uses the same frequency-pattern. Therefore, in two superframes the max. allowed number of 10 slots can be made available to serve temporary peak traffic, e.g., batch-arrivals of user data.

The resulting delay is represented by the curve denoted by "num. of multiple resv. <= 3" in Figure 6. As can be seen in this figure the delay can be decreased by more than 20 slots for a load of 200% and a threshold of 1. The resulting delay comes close to the delay for the idealized simulation assumptions. The additional delay for the realistic approach is less than one frame of 10 ms.

5. CONCLUSION

In this paper a new decentralized frequency division multiple access (dFDMA) approach for self-organizing networks has been presented. To organize the frequency usage two phases have been introduced. One phase, the so-called exchange phase, is used to organize the medium and reserve resources for transmission on arbitrary frequencies. During the second phase stations are allowed to explore *all* frequencies. Based on different frequency patterns and the introduction of the two phases an efficient usage of the available frequencies becomes possible. Even with low to moderate complexity of stations, which need only one transceiver, all resources in a framed and slotted system with several frequencies can be explored. Moreover, the new concept has been adopted to an air-interface for inter-vehicle communication, which has been developed within the project FleetNet, and its practicability and efficiency have been demonstrated. Regard that this approach is a trade-off between flexibility and efficient resource exploration on the one side and complexity in hardware and organization needed to guarantee specific requirements, e.g., broadcast of important messages, on the other side.

Future work will focus on performance evaluation of the dFDMA approach including the dimensioning of the system parameters. In addition, the application of this approach to other air-interfaces is one open topic and seems to be promising because of the generic concept for the simultaneous exploration of frequency channels.

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