On Traffic Dynamical Aspects of Inter Vehicle Communications (IVC)

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Abstract - **Inter Vehicle Communication (IVC) has become a major topic during the last few years. Within the FleetNet project a novel mobile ad hoc network will be developed - based on the UMTS Terrestrial Radio Access Time Division Duplex (UTRA TDD) air interface - to interconnect vehicles and vehicles with roadside gateways via a mobile Internet. In this paper we focus on the impact of vehicular traffic dynamics on protocols for ad hoc networks. Based on analytical treatment of vehicular traffic and on realistic traffic scenarios, we deduce requirements and their interdependencies for the developed ad hoc networking protocols, and verify them by simulation. We show that the proposed MAC and RRM protocols are suitable for Inter Vehicle Communication with its high dynamics in freeway environments.**

Keywords - ***Inter Vehicle Communication (IVC), Ad Hoc Networks, UTRA TDD, Vehicular Traffic Theory, Traffic Dynamics, Medium Access Control (MAC)***

I INTRODUCTION

Inter Vehicle Communication (IVC) has become a major topic during the last few years. Within the FleetNet* project [1] a novel mobile ad hoc network is developed to interconnect vehicles and vehicles with roadside gateways via a mobile Internet. Major services, supported by FleetNet will be road traffic telematics and mission critical services like emergency notifications and services for co-operative driver assistance, which put very high demands on the air interface and the used protocols. High relative velocities up to 500 km/h between oncoming vehicles in a highway scenario will lead to frequent topology changes, i.e. a very high network dynamic.

Within this work we will investigate and analyse the grade of topology changes in freeway environments and its impact on the protocols of FleetNet. We will concentrate on the protocols of the data link control (DLC) layer. To obtain estimations on traffic dynamics and protocol activities in FleetNet, results obtained from traffic simulations will be discussed and compared to analytical results presented in [2].

II FLEETNET PROTOCOLS FOR THE AIR INTERFACE

Mobile ad hoc networks do not depend on a given infrastructure. Thus, communicating devices cannot rely on access points or base stations acting as central controllers. They have to build the network in a self-organizing way. FleetNet will use a decentralized Medium Access Control (MAC) protocol together with a Radio Resource Management (RRM) scheme that is suitable for a scenario with frequent topology changes.

As the basis for the FleetNet air interface, UTRA TDD has been chosen for the following reasons [3]. Because of its code division multiple access (CDMA) component together with its frame and slot structure, UTRA TDD offers a high granularity and flexibility for asymmetric data transfer. It further provides a communication range of more than 1 km and supports high velocities up to 250 km/h. It has been shown in [4] that UTRA TDD is suitable for Intelligent Transportation System (ITS) applications and operation in ad hoc networks and it is proposed in [5], too.

As UTRA TDD is basically a technology for cellular mobile networks, MAC and RRM have to be modified or newly defined to support ad hoc networks with a decentralized MAC. To provide different service classes with different requirements on Quality of Service (QoS) the FleetNet MAC will provide different mechanisms to reserve transmit capacity. Besides permanently assigned parts of transmit capacity for high-priority services, resources can be dynamically reserved for services with lower priority. The standard UTRA TDD MAC protocol is using periodically recurring frames, which shall be maintained as basis for the ad hoc mode. The frame duration for the low-chip rate version is 10ms (cf. Figure 1) comprising 14 slots. In each of the slots up to 16 spreading codes can be used to transmit to one or several receivers.

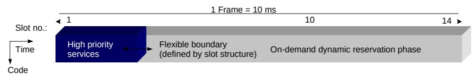

Figure 1: UTRA TDD ad hoc frame structure

The MAC frame is logically divided into two parts: one part for high priority services, where the minimum number of high priority slots, N_{high}, is a system parameter. The remaining part is called *on-demand dynamic reservation phase* and can be assigned and reserved dynamically by different stations for several services with lower priority. To gain access to the radio medium it is proposed that each station has to reserve a small amount of transmit capacity permanently, 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 signalling purposes but may also be used for the transmission of user data packets. For the initial reservation attempt of the CSBC, reservation ALOHA

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(R-ALOHA) is used [3]. When the CSBC does not provide enough capacity, it is used to transmit a reservation request by means of inband-signalling to reserve capacity in terms of a periodic time slot (cf. Figure 2). 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 capacity can be performed within a limited time until the next CSBC is available. The reserved capacity for user data packet transfer is only used and reserved by means of piggyback signalling as long as packets have to be transmitted and is released after successful transmission.

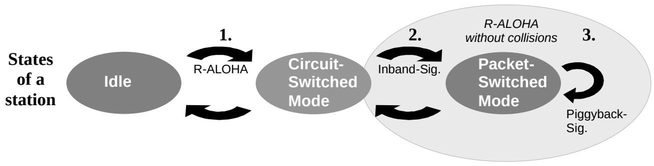

Figure 2: capacity reservation by means of CSBC

Generally, it has to be answered in this paper, if the developed dynamic reservation scheme is reasonable for FleetNet and its high relative velocities. A significant parameter for medium access in mobile ad hoc networks is the grade of topology changes. Topology dynamics will have impact on various parts of the protocols. The mean possible communication duration between vehicles will have impact on the amount of reservation messages transmitted. Furthermore, the grade of topology changes will affect the amount of reservation conflicts and collisions inside the system, if vehicles approach each other, which have reserved identical resources. Simulation of traffic scenarios and statistical investigations on the traffic dynamics shall give realistic estimations on possible communication durations and speed of topology changes. Our simulation results in Chapter IV will show that the MAC schemes with their reservation capabilities proposed for FleetNet are suitable for handling high traffic dynamics.

III ANALYTICAL INVESTIGATION OF TOPOLOGY DYNAMICS

Based on classical vehicular traffic theory, e.g. [6], we try to answer the questions outlined in Section II. In this paper the following two basic communication scenarios are considered [2]: a) all vehicles move in the same direction and b) oncoming traffic. For the different scenarios the possible communication durations between two vehicles are calculated. This gives a rough indication if the topology is approximately stable during a period of time that is long enough to make resource reservations reasonable.

A vehicle can either be within detection or communication radius of another vehicle. The detection radius defines the area where a transmission of any station can be detected, whereas the communication radius defines the area where a signal can be decoded with high probability. We first consider an undisturbed traffic scenario. Velocities of vehicles are constant, whereby the value of velocity is generally assumed as Gaussian distributed.

a) All vehicles are driving in the same direction:

From the Gaussian distribution the probability density function (pdf) $p_t(t)$ of communication duration can be calculated as:

$$p_t(t) = \frac{2 \cdot R}{s_{\Delta v}\sqrt{2p}} \cdot \frac{1}{t^2} \cdot e^{-\frac{\left(\frac{2 \cdot R}{t} - m_{\Delta v}\right)^2}{2 \cdot s_{\Delta v}^2}} \quad \text{for } t \geq 0 \qquad (1)$$

wherein R is the communication radius, and $m_{\Delta v}$ and $s^2_{\Delta v}$ are mean and variance of relative speed. Integrating Eq. 1 we get the probability distribution function (PDF) $P_t(t \leq T)$ of the communication duration, which is shown in Fig. 3 for average velocities between 30 km/h and 150 km/h and $R = 1$ km. Typical durations exceed 280 s for a relative speed of 30 km/h and 55 s for 150 km/h in 95% of the cases if vehicles are driving in the same direction.

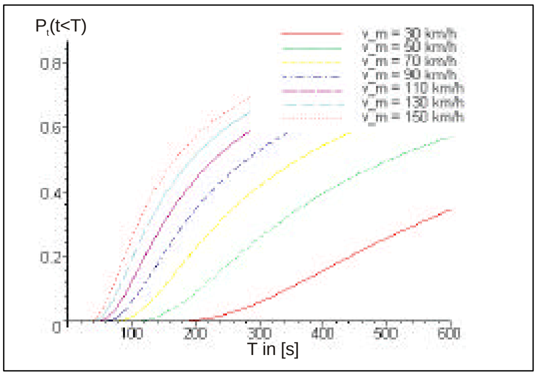

Figure 3: PDF of communication duration t_{comm}

b) Oncoming traffic:

For this scenario a similar equation to Eq. 1 can be inferred. From this we obtain the PDFs shown in Figure 4. With increasing speed the communication duration decreases as expected. Typical durations exceed 140 s for a relative speed of 30 km/h and about 30 s for 150 km/h in 95% of the cases if oncoming traffic is considered. Therefore, even for a mean velocity of 150 km/h there is a high probability to have communication periods with more than 3000 MAC-frames, which makes reservations reasonable for our simple scenario.

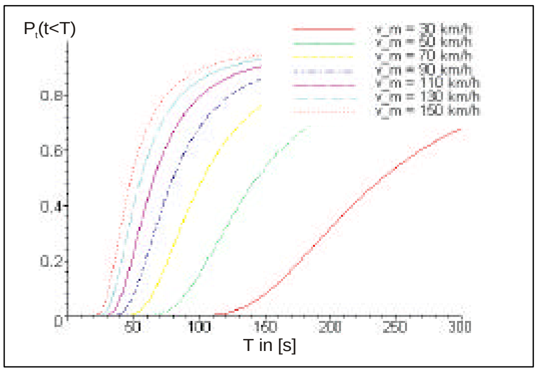

Figure 4: PDF of communication duration $t_{comm,on}$

IV SIMULATIVE INVESTIGATION OF TOPOLOGY DYNAMICS

To verify the analytical results, several simulations were made. The simulations are based on movement data produced by the traffic simulation tool DYNEMO [7] as well as on data retrieved from DaimlerChrysler simulations [8]. A special analysis program was developed, which processed the output of the DYNEMO and DaimlerChrysler simulations to create the depicted graphs.

A Communication durations in DYNEMO simulations

The traffic simulator DYNEMO comes up with the option to declare a certain velocity distribution function for the generated vehicles. As presumed in theory a normal distributed velocity distribution has been declared. For the analysis, several different traffic scenarios have been simulated with DYNEMO. For all simulations the average starting velocity is μ = 110 km/h with standard deviation $\sigma = 0.3\mu$. However, the velocities of vehicles change during simulation due to varying traffic density. The following three scenarios were investigated:

a) *All vehicles are driving in the same direction:*

The first scenario deals with a simple straight motorway section whereas one can differentiate between simulations with and without oncoming traffic. In the traffic situation showed in Figure 5 vehicles depart from node 1 with a density of 1000 veh/h. The length of the motorway is set to 87,5 km. Vehicles that reach node 2 are eliminated from the simulation. The total duration of the simulation amounts to 7200 s (7200 time steps). The calculation of the average communication duration distribution function involved data of about 100 vehicles. The analysis results in a communication duration PDF as depicted in Figure 6.

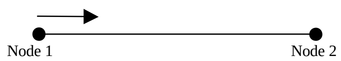

Figure 5: traffic scenario a)

Obviously either graphs are quite related whereas the simulation distribution does not match the theory curve exactly. One point is that the probability of short communication durations in the simulation is slightly higher than in theory. Another reason is, that if a vehicle is created in the simulation, numerous vehicles already exist inside its communication range. Therefore, their communication durations are shorter than assumed in theory since they do not enter and leave the communication range as intended.

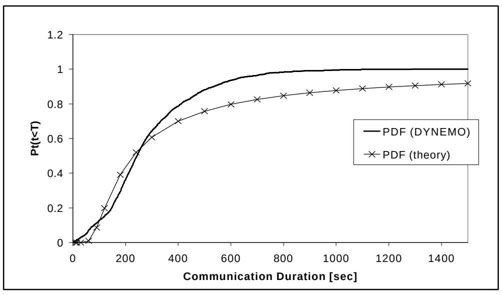

Figure 6: PDF of communication duration in scenario a)

b) *Oncoming traffic:*

In the second scenario the vehicles depart from both nodes (1 and 2). At node 1 vehicles are generated and thus departed with a density of 1000 veh/h, from node 2 a density of only 25 veh/h is applied. With a section length of 157,5 km the simulation duration has been 9000 s. The analysis resulted in a communication duration PDF as depicted in Figure 7.

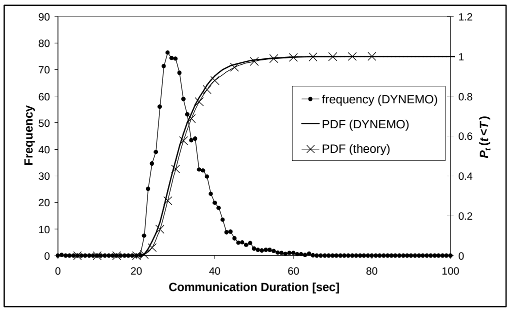

Figure 7: PDF of communication duration in scenario b)

The above figure shows the simulation results for scenario b). From all simulated vehicles a set of eight has been chosen to analyse communication durations. Communication durations of these vehicles with all oncoming vehicles are measured. The superposition of the results of these eight vehicles leads to the graphs named “DYNEMO”. From the graphs it can be seen, that for oncoming traffic the minimum simulated communication duration is about 20 seconds, which means a minimum of 2000 MAC-frames (and even with the starting effects of scenario a) depicted in Figure 6 a communication duration of 50 seconds is exceeded with a probability of 95%).

c) *Crossed motorway sections*:

In this enhanced scenario two separate motorway sections have been crossed (cf. Figure 8). From node 1 and node 3 vehicles are generated with a density of 1000 veh/h. Thus there is no direct oncoming traffic. Since both sections were separated, only straight traffic is possible. Section 1 (node1 – node 2) has a length about 157 km, section 2 (node 3 – node 4) is about 128 km long.

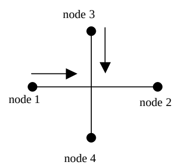

Figure 8: traffic scenario c)

Figure 9 shows the corresponding PDF of section 1 which is nearly identical to the PDF of section 2. The figure shows the communication duration distributions in a more real-life scenario. Here the graph is composed of the superposition of the communication durations of vehicles with the same driving direction as well as of the durations between the reference vehicle and vehicles that drive on the other section. These graphs are not any more closely related to any of the theory curves. As one might have expected the resulting graph is located in-between both theoretical curves, which portray a kind of border. This result becomes more obvious if we consider the vehicles that drive on the other section as oncoming traffic, approaching at a lower speed than directly oncoming traffic. Thus, for this scenario one could introduce a factor to weight the influence of this inflow. This circumstance makes the simulation graph drift away from the right border (indicates inter-vehicle communication in the same direction) to the left (oncoming traffic). It is also remarkable that we have a relatively high offset at the beginning of the simulation graph. As indicated earlier this is influenced by vehicles popping up inside the communication radius close to the edge and thus possibly leave it very early. For non-constant velocities this could be the result of vehicles that shortly enter the radius, then slow down (or the reference vehicle increases its speed) and immediately leave the range. One possibility to reduce this effect might be the introduction of a hysteresis, i.e. a range that has to be passed to re-enter or leave the communication radius.

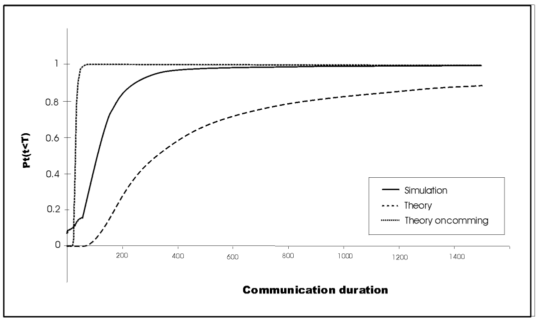

Figure 9: PDF of scenario c) section 1

B Communication durations in DC simulations

In the following section we have a look at analysis results of several DaimlerChrysler (DC) simulations. In these simulations a microscopic traffic simulator was used, based on detailed models of different vehicle types (including trucks) and different driver behaviours.

In the following graphs there is a distinction between *Theory* and *Theory 100%*. The first curve illustrates the theoretical values as derived in [2]. Since the accomplished simulations were restricted in simulation time, very high communication durations could not be met. That is why the latter graph, where the maximum simulation communication duration has been used to normalize the graph, depicts the theoretical values.

Figure 10 depicts the analysis of a simulation in which vehicles move at an average speed of 145 km/h, furthermore 25% of the vehicles are trucks with an average speed of 90 km/h. Vehicles move only in one direction, i.e. no oncoming traffic is involved. A single motorway section has been simulated with a total section length of 30 km.

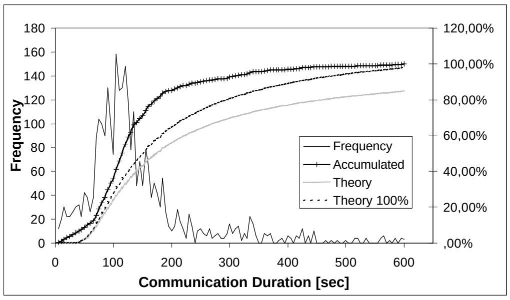

Figure 10: DC trace with no oncoming traffic

As one can see in the figure the compliance of theory and simulation results is not very high. Since the simulation duration just amounted to approximately 700 s, whereas as an example transition time for the 2000 m communication scope for vehicles with a velocity difference of 10 km/h already computes to 720 s, this deviance can be explained. Furthermore, only 83 vehicles have been produced. Thus, the number of vehicles does not suffice to emulate proper normal distributions. In addition, the theoretical calculations did not include changing velocities, whereas that was the case in the DC simulations (vehicles accelerate and decelerate). This leads to a lot more shorter communication durations.

Figure 11 depicts the analysis of a simulation where oncoming traffic is involved. The same scenario as in the previous simulation was used, whereas in this situation the number of cars has been tripled.

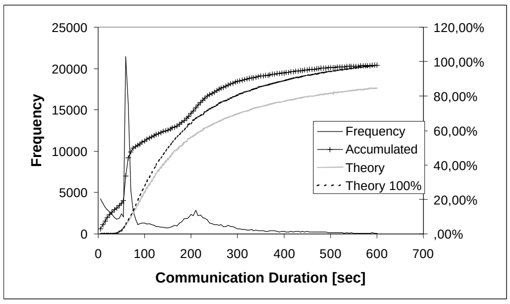

Figure 11: DC trace with oncoming traffic

As we see in this figure the graphs of oncoming traffic and traffic with the same driving direction are superposed. This can be seen by looking at the Frequency graph in Figure 11. Here the total number of communication relations ordered by its duration is shown. The first maximum of the frequency curve (~60 s) indicates communication durations of oncoming vehicles, whereas the second (~200 s) describes the durations for vehicles with the same direction. To be able to compare these analysis results more precisely with the theoretical formulas, Figure 12 shows the analysis of only the vehicles driving in the same directions and Figure 13 shows the analysis of a simulation of oncoming traffic, where the communication durations of vehicles driving in the same direction have been deleted.

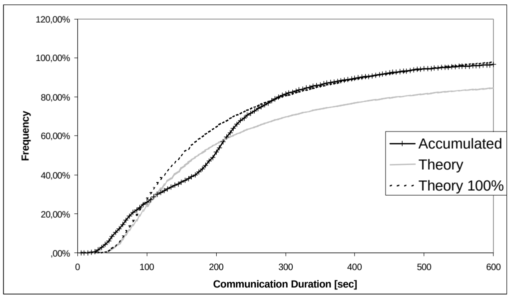

Figure 12: traffic part with same directions

As one can recognise, despite of the relatively small amount of vehicles and the short simulation duration, the analysis results of this simulation almost correspond to the theoretical values.

The analysis of the DaimlerChrysler simulations reveals another aspect of oncoming traffic. As expected, the total number of communication relations is much higher, if no separation of both driving directions is included. In Figure 10 83 vehicles have about 160 communication relations of roughly 100 s. In Figure 13 250 vehicles have about 300000 communication relations lasting about 40 s. Thus, with no separation of driving directions a very large number of attempts to communicate has to be handled.

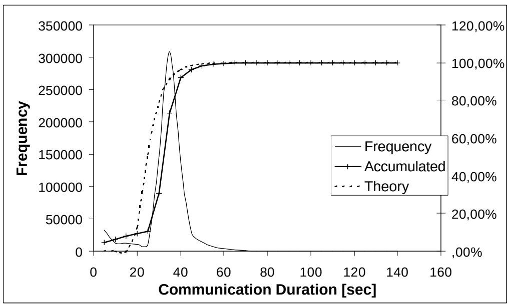

Figure 13: oncoming traffic part

V SUMMARY AND CONCLUSION

In this paper we focused on the impact of vehicular traffic dynamics on protocols for ad hoc networks. Based on analytical treatment of vehicular traffic and on realistic traffic simulations, we investigated possible communication durations between two vehicles. The analytical investigations made in [2] were checked with simulative results. We showed with our simulations, that even with oncoming traffic and high relative velocities, we have communication periods with at least 2000 MAC-frames, which makes reservations reasonable for our scenarios.

The comparison of the theoretical and the simulative results lead to the following statements:

- Performing simulations based on real traffic models, one has to consider starting effects, where vehicles enter and leave communication range quickly. The probability of very long communication durations may decrease significantly.
- In addition, effects resulting from vehicles driving close to the edge of the communication range and thus possibly enter and leave it frequently because of a changing velocity, have to be considered. This may lead to a higher probability of very short communication relations. The introduction of a hysteresis should solve this problem.

Simulation results show, that Eq. 1 and its counterpart for oncoming traffic can give a rough indication for possible communication durations between two vehicles. Although communication durations are shorter in real life scenarios than in theory, it has to be emphasized, that in communication scenarios, where the focus is basically on vehicles that are driving in the same direction, the situation is much more relaxed.

Running an ad hoc network in an inter vehicle communication scenario seems to be very challenging, regarding the very high dynamics and frequent topology changes. However, the use of UTRA TDD as the air interface for FleetNet gives us enough flexibility to handle these dynamics. The presented calculations and simulations show that MAC and RRM scheme proposed for FleetNet can handle the requirements that come from realistic traffic scenarios in freeway environments as the communication durations between arbitrary stations typically exceeds 2000 MAC frames. Consequently, reservation based schemes as proposed for UTRA TDD ad hoc are feasible.

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