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FLEETNET: BRINGING CAR-TO-CAR COMMUNICATION INTO THE REAL WORLD

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Abstract. Car-to-car communication by means of wireless technology shows a strong potential to enhance both safety and comfort of road users. The necessity to reach cars beyond the transmission range of the own radio creates the challenge to find algorithms to efficiently forward packets.
In these so-called vehicular ad hoc networks, position information has been identified as a crucial component that alleviates some of the limitations of existing topology-based protocols. Thus, we see the use of positional information at the core of a car-to-car communication system that provides advanced applications for active safety, distributed floating car data, as well as user communication and information.
A major thrust to leverage a car-to-car communication platform was provided by the *FleetNet* project, partly funded by the German Ministry of Education and Research BMB+F[†] and led by DaimlerChrysler AG. Based on ad-hoc networking principles and the availability of position information, the project developed suitable communication concepts. In addition to simulation studies, a prototype communication and application system was implemented and deployed, embedding safety and convenience applications. With car-based real world field trials successfully conducted, first results and experiences look promising.

1 Car-to-Car Communication as the Key to Safety

For drivers of vehicles, information about their immediate vicinity is crucial for being able to drive safely. So far most information is gathered by direct visual observation and in response to sounds. Some enhanced information on road conditions is available via radio warning, and navigation support is also becoming state-of-the-art. Recent strategies to improve the driver's safety are the *BMW Connected Drive* [2] initiative, the *Vision of Accident-Free Driving* by

[†] Project FleetNet, www.fleetnet.de, under grant BMBF 01AK025

DaimlerChrysler [3] and the work of the *Vehicle and Infrastructure Integration (VII)* [1, 7] task force of the US Department of Transportation.

Driver safety has been recognized as an important challenge by almost all major players in the automotive industry and by governments in many countries. 450,000 road accidents per year in Germany and three times this number in Europe with an annual fatality figure of 42,000 (1999) are good reasons to take safety very seriously. This has led to increased efforts to search for solutions making use of the newest technological advances available and to the launch of various national and supranational research projects.

While today's cars use systems that are able to sense their environment, these systems do not actively exchange information among vehicles as well as among vehicles and the roadside by wireless communication. Hence, data collected by a vehicle are not available in others. The vision of vehicle-to-vehicle and vehicle-to-roadside communication is that information available in cars, such as from sensors and instruments, can be quickly passed on to others in the immediate vicinity, by means of ad hoc network communication. The extension of sensory information allows drivers to react more quickly to emergency situations, e.g., cars ahead braking. Communication of vehicles with the roadside using the same basic technology provides additional information towards convenience and comfort, such as special offers available along the motorway.

In this paper we report on our efforts in the field of inter-vehicle communications carried out over the last couple of years primarily within the framework of the *FleetNet* project. Starting with the concept of position-based forwarding, we have shown by means of network simulation that this concept has benefits for use in vehicular environments. Based on the results from network simulations and a software prototype implementation of a position-based router, we have gained first experiences from measurements in a real-world testbed for car-to-car communication.

The remaining sections of the paper are structured as follows: After presenting the *FleetNet* approach for position-based forwarding in Section 2, we summarize the results from our simulative protocol evaluation in Section 3. In Section 4 we describe the software prototype implementation. In Section 5 we report on first real-world experiences of the system based on measurements, and finally give an outlook on our future work in Section 6.

2 Position-Based Forwarding – The FleetNet Approach

Car-to-car communication allows direct communication between any two cars if direct wireless connectivity exists. In the case of no direct connectivity, multi-hop communication is used, where a data packet is forwarded from one car to another until it reaches its destination. Figure 1 shows an exemplary scenario where vehicles are warned of an approaching construction site and also have Internet access through an roadside gateway. It is common to all applications using multi-hop communication that routing is a particularly challenging task for vehicular ad hoc networks: on the one hand, due to high dynamics and frequent topology changes a high degree of adaptivity is required. On the other hand, the routing approach must be scalable with respect to the high number of cars that potentially communicate in highway or city environments.

In order to meet the requirements for adaptivity and scalability, position-based forwarding has been chosen as a promising basis for ad hoc network organisation. The general idea of position-based forwarding is to select the next hop based on position information such that the packet is forwarded in the geographical direction of the destination *(greedy forwarding)*.

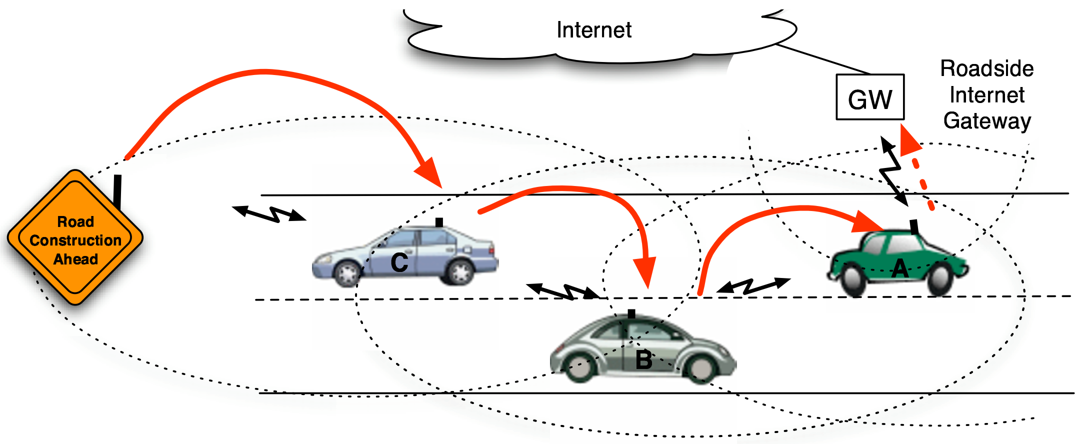


Fig. 1. Multi-hop Car-to-Car Communication

This forwarding decision is determined by means of the destination's position contained in the packet header, the car's own position and the position of the neighboring cars. Position-based forwarding enables communication from one car to another (one-to-one), but also delivery of data to cars located in a geographical area. The latter approach, *geocast*, is of particular importance for applications in vehicular networks, where data is typically sent to all cars in a geographical area (geographical broadcast, e.g., for emergency warning) or information from any car in a geographical area is retrieved (geographical anycast, e.g., for distributed floating car data).

The main benefit of position-based routing with respect to existing topology-based routing is the fact that no global route from the source to the destination must be created and maintained [12]. Unlike topology-based routing, the forwarding of data packets in position-based routing is made on a per packet basis. Therefore, no hop-by-hop route must be created in each router and forwarding decisions about the next hop are performed exactly when needed (instead of the point of time when the route is created). Thus, the term 'routing' should not be misunderstood to be synomym to building routes but could be also rephrased as 'forwarding'. The costs of the approach are the availability of GPS or other positioning systems and a system for dissemination and management of position information in the ad hoc network.

3 Simulative Protocol Evaluation

In order to evaluate various ad hoc routing approaches with respect to their applicability for vehicle-to-vehicle communication, we have made use of realistic vehicular movements patterns for highway and city scenarios. These movement patterns were generated by DaimlerChysler using their vehicular traffic simulation facilities (see [4, 5] and [11]) and show highly realistic microscopic and macroscopic properties. These movement scenarios were used as input to the ad-hoc network simulations performed with the network simulator ns-2 [14].

For the highway scenarios, we compared greedy position-based routing making use of the Reactive Location Service [9] with Dynamic Source Routing [8], a purely topology-based ad hoc routing approach. As expected, the feature of not requiring 'routes' and corresponding setup and maintenance procedures, but forwarding packets 'on the fly' gives position-based routing a strong competitive edge in these highly mobile scenarios. The pseudo-one-dimensionality of highway scenarios also leads to an equivalence of observing a network partition and reaching a local optimum with respect to the 'greedy forwarding' criterion.

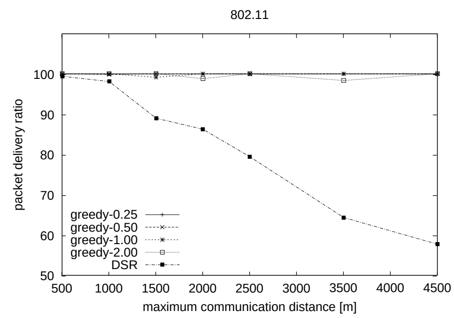


Fig. 2. Exemplary Simulation Result: Average Delivery Rate vs. Communication Distance

Figure 2 depicts an exemplary simulation result for position-based greedy forwarding (denoted as greedy) and DSR in a highway scenario. Here, different simulation runs were carried out with different distance between the communication partners. In addition to that, only node pairs were chosen that had connectivity during the communication process, i.e., they were in each others transitive hull w.r.t. to the unit disk graph model. With the 'greedy' protocol, the nodes use beacons to exchange position information and we have varied the beacon interval between {0.25,0.5,1,2} seconds, while the the transmission range stayed constantly at 250 meters. The figure indicates that the packet delivery ratio of DSR is decreasing stronger with an increasing communication distance. Greedy forwarding, however, copes quite well with its task exploiting the knowledge about the neighbors positions (see [4] for a more complete description of the results).

In city scenarios, however, simple greedy forwarding fails most of the time since the position information points into the right direction but is not correlated with available paths (streets) to the destination. Recovery strategies, as proposed in the literature, could not be successfully applied for the city scenarios since these scenarios did not match the assumptions under which the recovery strategies were developed [11]. By making use of digital maps and introducing a combined position- and map-based routing approach, we obtained very good results compared to other routing strategies. The combination of position- and map-based routing essentially takes the best of both worlds – position-based and topological-based ad hoc routing – but clearly imposes higher requirements to the routing system.

4 Implementation and Demonstration

In order to get real-world experiences and to provide a proof-of-concept we have implemented the position-based routing protocol [6]. The implementation was carried out as a user-space daemon in the Linux operating system for x86 computers. With respect to the ISO OSI communication model the FleetNet routing in fact represents a 'layer 2.5' approach, where an additional routing header is put between the wireless packet header and IP header.

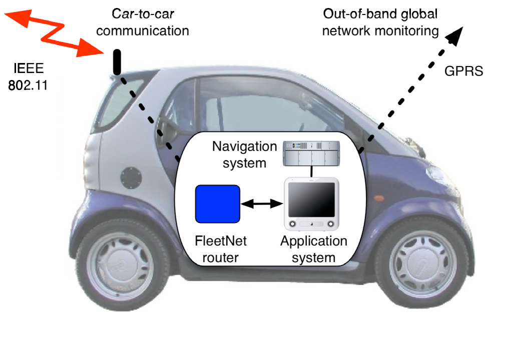


Fig. 3. System Architecture of a Demonstrator Car

Using our software prototype we have set up an experimental test network. It is based on six `Smart`^{TM} cars, each equipped with a Linux-based FleetNet router, i.e., a notebook with a 802.11b[‡] wireless LAN PC card, and an external planar antenna with a gain of 4 dBi. As depicted in Figure 3, a standard 100 MBit/s Ethernet connects this router to a dedicated application system providing an audiovisual interface to the (co-)driver. In addition, it gathers position information from the on-board navigation system and feeds it to the router. To support global monitoring of the 802.11-based ad hoc network, each car is additionally equipped with a GPRS network interface connected to the central "showroom". The implementation and experimental test network have been successfully demonstrated in real-world environments using up to six cars.

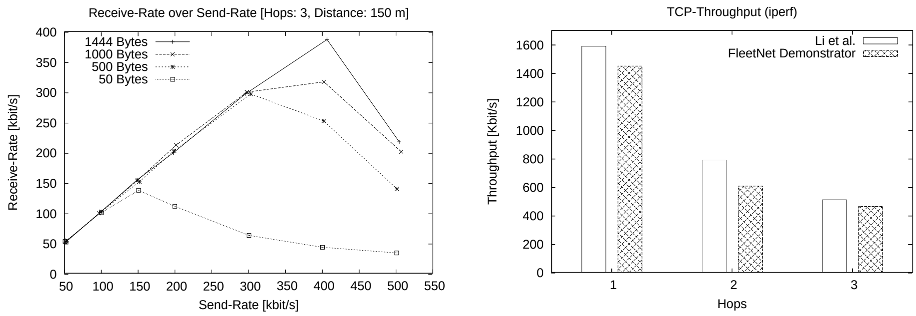
5 Practical Experiences

In addition to application testing, we have conducted some experiments to get an initial estimate of the network performance [13] with currently available standard radio hardware. However, these measurements should only be seen as a starting point for extensive field studies.

The first type of measurements we undertook were simple single-hop trials with static nodes. These experiments – performed at different node distances and with different packet sizes – were done mainly to understand the performance limit of direct communication. In the context of multi-hop forwarding, this proved to be essential as a building block for further studies. As described in [13], the results were both reassuring and interesting. On one hand, we could demonstrate stable sustained data transmission between two cars over 500 meters[§]. On the other hand, the impact of "environmental factors" like passing cars showed to be significant. Thus, more complex measurements of this kind should be undertaken, especially for other frequency band and modulations schemes like with 802.11a.

‡ While most of the trials were done using 802.11b, the system was also shown to work with 802.11a.
§ For all measurements presented here, the gross 802.11b (unicast) data rate was set to 2Mbps.

Trying to understand the impact of packets of the same flow competing for the radio channel (as shown simulatively in [10]), multi-hop measurements were conducted – again without mobility. To do this, we have used four cars that communicate via three hops. The cars are positioned with a distance of approximately 150 to 250 meters between neighboring vehicles (see Figure 5(a)). We have conducted measurements with UDP and TCP. For UDP, packets of different sizes are sent from the first to the last car of the chain and an acknowledgment is sent back to source. For the TCP performance, we perform data transfers with long-living TCP connections using the network measurement tool *iperf*.



(a) UDP Throughput (b) TCP Throughput

Fig. 4. Static 3-Hop Throughput Measurements

Figure 4(a) shows the UDP throughput we were able to achieve doing the multi-hop measurements. As expected, the maximum achievable UDP throughput depends on the packet size culminating with the biggest packets. However, the figure also shows that an over-saturation of the channel results in lower-than-maximum end-to-end throughput. This is due to the fact that the packets exceeding the optimal sending rate tend to destroy other transmissions and thus decrease overall throughput, and to the hidden terminal problem.

The TCP performance is illustrated in Figure 4(b), which reflects the TCP throughput over the number of hops. We have measured a TCP throughput of approximately 450 kbps over 3 hops. For comparison, the figure includes the simulative and experimental results of Li et al [10], which confirms our measurements. Although the experiments are not directly comparable due to different evaluation settings (e.g., hardware equipment, distance of nodes), the results show a similar trend.

Finally, we performed dynamic multi-hop measurements with a convoy of four cars driving along an approximately 5 km circular road shown in Figure 5(b). The circuit covers a typical suburban area including intersections, traffic lights, fast lanes and passing traffic. For communication, data packets of a predefined size and at a predefined rate are sent from the last car to the first car. When a packet reaches the end-to-end recipient (the first car) it is acknowledged with an ACK packet carrying the data packets' sequence number.

At the beginning of each run, all the cars are in transmission range of each other. During the run, the distance of the cars in the convoy is increased up to the point when only 3-hop

(a) Setup for Static 3 Hop Scenario

(b) Map of the Circuit for the Dynamic Measurements With 3 Hops

Fig. 5. Static and Dynamic Multi-Hop Measurements

forwarding can achieve end-to-end connectivity. However, the results shown in [13] indicate that while the forwarding basically worked, realistic street environments are demanding on the overall system. In order to further understand and to tune the estimated system performance limitations, we will conduct additional measurements.

To summarize, the presented practical experiences outline the capabilities of position-based communication in vehicular multi-hop ad hoc networks. Even under realistic conditions with "real" position information, "real" radio channel situation and real vehicle movements restricted by street traffic, the network operates successfully. However, the gathered results show great potential for optimization and need for further investigations.

6 Conclusions and Outlook

We regard car-to-car communication as a promising technology that will considerably improve the driver's safety and comfort. While the today's safety systems basically provide a sensing of the vehicle's environment, with car-to-car communication the vehicles are able communicate by means of multi-hop communication among each other and with road side gateways for Internet access. Within the research project *FleetNet* we have conducted a feasibility study to bring a car-to-car communication system from an idea into the real world. Starting from the idea for a vehicular ad hoc network by using geographical positions for communications in a vehicular ad hoc network, we were able to show the benefits of this approach by means of network simulations. In fact, we have used complementary methods – network simulations to investigate scalability issues for large-scale networks and measurements for evaluation of our approach in realistic environments. With the implementation of a software prototype and its integration into a real test network of cars, we could gain first experiences from real world tests by means of measurements.

In order to develop car-to-car communication to a mature technology, we are in the process of enhancing the communication protocols using a cyclic approach of modeling, simulation, implementation, and measurements for continuous and sustainable improvement. This approach facilitates a cyclic revision of mechanisms, but also a continuous enhancement of simulation models for wireless environments and data traffic patterns based on measurements. In particular, we investigate fluctuating radio conditions in real-world environments that can result in frequent topology changes. We aim at improving the 'robustness' of the system against such conditions. The development of recovery strategies for forwarding in 2-dimensional scenarios with radio obstacles (e.g. cities) in vehicular ad hoc networks represents another field for enhancements. Moreover, the reliable transport of data in multi-hop communication in presence of packet losses due to error-prone wireless links and topology changes, congestion control in the network, and routing security are other targets for the future.

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