Information Dissemination in Self-Organizing Intervehicle Networks

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***Abstract*—Intervehicle communication (IVC) is an emerging topic in research and application that is getting increasing attention from all major car manufacturers. In this paper, a novel method for scalable information dissemination in highly mobile *ad hoc* networks is proposed: segment-oriented data abstraction and dissemination (SODAD). With SODAD, information can be distributed in an information range multiple orders of magnitude larger than the transmission range of the air interface, even if only 1%–3% of all vehicles are equipped with an IVC system, e.g., during market introduction. By restricting the method to the dissemination of map/position-based data, scalability is achieved. In the second half of this paper, an example application for the SODAD method is presented: a self-organizing traffic-information system (SOTIS). In SOTIS, a car is equipped with a satellite navigation receiver, an IVC system, and a digital map. Each individual vehicle collects traffic information for its local area. Using the digital map, the traffic information is analyzed based on road segments. By distributing the information in the *ad hoc* intervehicle network using the SODAD method, a decentralized traffic information system is created. The performance of the proposed methods is evaluated using network simulation with vehicular mobility models. Simulation results for typical scenarios are presented. Furthermore, a prototype implementation based on commercially available standard hardware demonstrates the feasibility of the proposed approach.**

***Index Terms*—Car-to-car communication (C2CC), data dissemination, intervehicle communication (IVC), traffic-information system, vehicular *ad hoc* network (VANET).**

I. Introduction

THE integration of communication technology in state-of-the-art vehicles has begun years ago: Car phones and Internet access based on cellular technologies as well as Bluetooth adapters for the integration of mobile devices are popular examples. However, the direct communication between vehicles using an *ad hoc* network,[1] referred to as intervehicle communication (IVC) or car-to-car communication (C2CC), is a relatively new approach.

Compared to a cellular system, IVC has two key advantages.

- **Direct communication:** Since the vehicles communicate directly without any intermediate base stations, the communication delay[2] is low. In contrast to cellular systems, IVC is also suitable for the distribution of time-critical data such as emergency notifications in the area of an accident. Furthermore, vehicles can communicate even in rural areas not covered by cellular systems—the communication network is established by the cars themselves and available everywhere.
- **No service fees:** IVC requires no communication infrastructure or service provider. Service charges are completely avoided.

A. Applications for IVC

The specific properties of IVC allow the development of attractive new services. Some currently discussed examples in the two most relevant areas safety and comfort are as follows.

1) *Comfort Applications*: This type of application improves passenger comfort and traffic efficiency and/or optimizes the route to a destination. Examples for this category are: traffic-information system, weather information, gas station or restaurant location and price information, and interactive communication such as Internet access or music downloads.
2) *Safety Applications*: Applications of this category increase the safety of passengers by exchanging safety relevant information via IVC. The information is either presented to the driver or used to activate an actuator of an active safety system. Example applications of this class are: emergency warning system, lane-changing assistant, intersection coordination, traffic sign/signal violation warning, and road-condition warning. Applications of this class usually demand direct vehicle-to-vehicle communication due to the stringent delay requirements.

The focus of this paper is on information dissemination for comfort applications—safety applications will not be considered.[3]

B. Technical Challenges

Applications that make use of IVC face two major challenges: required penetration and scalability. With low market penetration, in the majority of the time there is no or only a very limited number of communication partners within transmission distance. Therefore, the average range in which information can

Manuscript received February 23, 2004; revised June 23, 2004. This work was supported by the German project FLEETNET, which was funded in part by the German Ministry of Education and Research. The Associate Editor for this paper was H. Mahmassani.

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Digital Object Identifier 10.1109/TITS.2004.842407

[1]This specific type of *ad hoc* network is also known as the vehicular *ad hoc* network (VANET).

[2]This is for single-hop communication.

[3]Due to their stringent requirements on reliability and delay, we assume that safety applications solely based on IVC will not be feasible until a large market penetration is achieved.

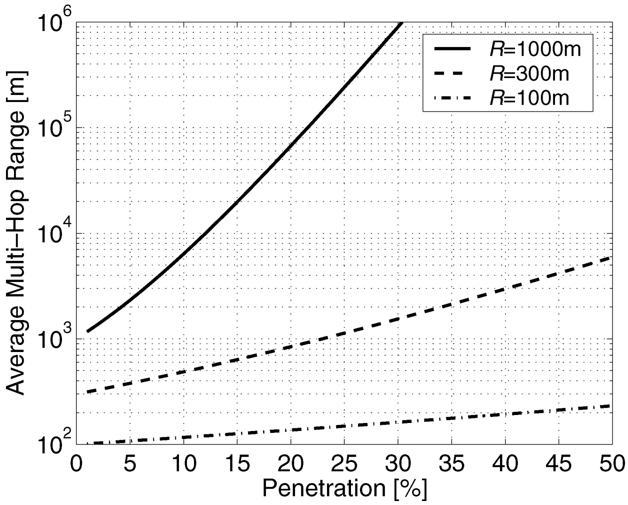


Fig. 1. Expected value of the multihop range (traffic flow volume: 900 vehicles/h/lane).

be distributed by (multihop) communication is small. This is illustrated in Fig. 1, where the expected value of the multihop range on a 2×2 lane highway is shown for a traffic density of 7.5 vehicles/km/lane and a velocity of 120 km/h. (The calculation of this expected value is outlined in the Appendix.) Here, R denotes the assumed transmission range of the air interface; the assumed penetration of the *ad hoc* communication system is varied in a range from 0% to 50%.

It can be seen that a penetration of 15% is required to achieve an average multihop range of 20 km in this highway scenario. Such a high ratio of equipped vehicles[4] will not be available when an IVC system is being introduced. Even if such a high number of vehicles equipped with the *ad hoc* communication system is achieved, a successful end-to-end communication requires that the multihop connection is available long enough for the data exchange and that successful routing is performed on time. This is very challenging due to the highly dynamic environment in vehicular scenarios.

Scalability becomes an issue once a higher market penetration is reached. In order to avoid overload conditions, the amount of data transferred needs to be restricted.

To solve these two challenges, segment-oriented data abstraction and dissemination (SODAD), a method for data dissemination for comfort applications, is proposed in this paper. SODAD can be used to create a scalable decentralized information system that can provide data in an information range multiple orders of magnitude larger than the transmission range of the air interface even if only 1%–3% of all vehicles are equipped with an IVC system. The advantages of the proposed approach are demonstrated by a novel self-organized traffic information system (SOTIS), which offers very detailed traffic information for the local area of a vehicle.

This paper is organized as follows. Section II gives a brief overview of related work. In Section III, the SODAD approach is described. A typical example application is presented in Section IV with the SOTIS application. The performance of SODAD and SOTIS is evaluated in Section V. The basic system is extended in Section VI with an adaptive broadcast mechanism, which significantly reduces the required data rate. A prototype implementation of SOTIS is presented in Section VII. Section VIII concludes this paper with a short summary.

[4]In the following, the term *node* will be used synonymously with *equipped vehicle*.

II. Related Work

Early research on IVC began in the 1990s, inspired by research in the area of intelligent transportation systems (ITS) initiated by the Department of Transportation (DOT) in the U.S. and by the PROMETHEUS project of the EUREKA program funded by the European Commission. With the decreasing cost of components for communication and positioning [e.g., global positioning systems (GPS)] in the recent past, IVC became more attractive. Various research projects were initiated [1]–[3], some explicitly focused on IVC, others considering IVC as one of many possibilities for data distribution. Increasing interest in roadside-to-vehicle communications and IVC also led to various standardization efforts worldwide, e.g., for a suitable air interface [4].

The approach of using IVC for disseminating (traffic) information among vehicles has been investigated by several other authors. In general, two different approaches can be distinguished: flooding the local area (limited by the number of hops or geocast) of the vehicle or using an *ad hoc* routing mechanism to establish a connection from one vehicle to a vehicle further ahead.

An example for the flooding technique is [5], where hop-limited flooding is used for the dissemination of traffic information. Additionally, a layered data structure allows a forwarding node to reduce the size of a data packet by discarding information. The idea is to exploit the fact that the required accuracy of traffic information is distance dependent, which is done similarly in the work presented in this paper. The system proposed in [6] also uses hop-limited flooding, but maintains a set of neighboring nodes and known senders of the message. If no neighbor for forwarding the message is in range, the message is stored until the set of neighbors changes.

Ad hoc routing-based approaches are proposed, e.g., in [7]–[9]. In [7], modifications of *ad hoc* on-demand distance vector (AODV) routing for vehicular environments are discussed. Reference [8] presents a beaconless routing protocol for highly dynamic network topologies. Carnet [9] is a location service for geographic routing in vehicular networks. However, as noted in Section I, the information range achieved with routing-based approaches is limited by the multihop range and, thus, rather short in cases of a low density of equipped vehicles.

Compared to the previously mentioned approaches, the method proposed in the following is different in various aspects: The transmission and reception of data packets is completely decoupled, no routing is required, and the rate at which a node sends data packets is adapted to the local environment.

III. SODAD

SODAD is a technique for the efficient information dissemination in intervehicle networks. It is suitable for a wide range of comfort applications, e.g., traffic information systems, parking

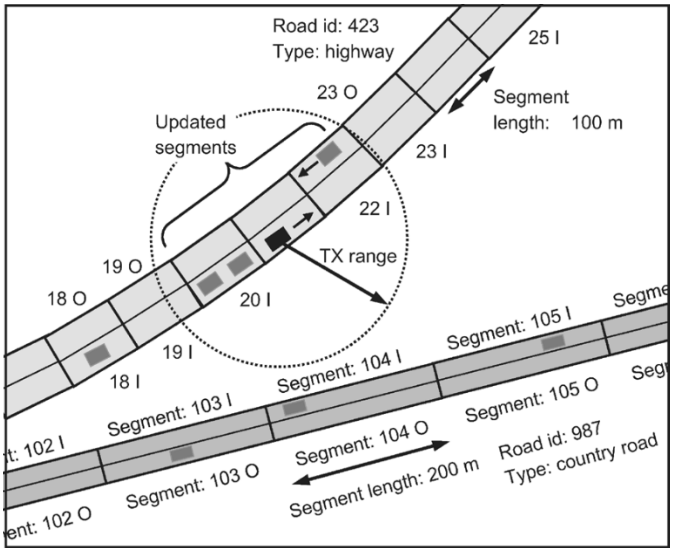


Fig. 2. Example for map-based data abstraction by segmentation of the roads in the local area.

lots, motel or gas price information, peer-to-peer travel information, and many others. This section describes the SODAD method and its basic ideas.

A. Map-Based Data Abstraction

Data distributed in a vehicular information system typically has the following properties.

- It has a spatial component, e.g., since it describes the situation at a specific location.
- The relevance for a receiver decreases with increasing distance to the location where the data was originally generated. (For example, in general, the interest of a driver in price information of a gas station nearby is higher than for a gas station 100 km away.) This also means that delay and reliability constraints become more relaxed with increasing distance.

These properties are exploited in SODAD: It is assumed that each vehicle is equipped with a digital map. The map is divided into segments of a known length, which can vary based on the type of object (e.g., road) that is considered.

Fig. 2 shows an example in which a vehicle driving on a highway chooses the road-segment length automatically and adaptively: A segment length of 100 m is chosen for the highway on which the car is driving and a larger segment length of 200 m is selected for the country road. The optimal segment size depends on application and road type; decreasing the segment size increases the level of detail of available information, but also leads to a higher data rate. Due to the digital map and a standardized selection of the segment size, each segment can be identified by an unique identifier (segment ID), e.g., the combination of road ID plus segment number plus direction.

Each node[5] generates new information for all segments in transmission range. This is done either by sensing the information itself or by receiving information observed by other vehicles. In the data-abstraction process, a data-aggregation function is applied: If N information values $d_1, d_2, \ldots, d_N$ have been received/sensed at node n for a segment i, the new information value $s_{n,i}$ is calculated by applying the aggregation function $a(\cdot)$

$$s_{n,i} = a(d_1, d_2, \ldots, d_N). \tag{1}$$

The nature of the aggregation function depends on the application; for example, the mean of $d_1, d_2, \ldots, d_N$ can be calculated or the maximum can be chosen. Additionally, a time stamp $t_{n,i}$ is set to the current global time (obtained via GPS). The tuple $(s_{n,i}, t_{n,i})$ completely describes the information available for a segment at a node.

This process leads to the scalability of the information system: Only one tuple $(s_{n,i}, t_{n,i})$ per segment is distributed. By using an adaptive broadcast scheme (Section VI-B), vehicles adapt their transmission behavior based on segment information broadcast by other nodes. Overload conditions are avoided and the data rate for an application is the result of segment length, area to be covered, and the frequency with which the per segment information changes. A higher number of equipped vehicles improves the accuracy and decreases the delay with which data is distributed, as outlined in the following sections.

B. Data Dissemination

The second part of SODAD is the dissemination of per-segment information by using the wireless link. The main objective is that data dissemination over large distances is achieved, even in cases of low penetration or low density of vehicles. Therefore, the wireless communication is based on two principles.

1) **Local Broadcast:** All data packets are transmitted in the form of local (1-hop) broadcasts. Nodes are never directly addressed and no routing of data packets in the traditional sense (i.e., on the network layer) is performed.
2) **Application Layer Store-and-Forward:** Since all data is sent in form of one-hop broadcasts, the application is responsible for forwarding the per-segment information. Information received at a node is always analyzed and compared with the currently available information. Only if it is still relevant and more accurate than the previously known information, it will be stored onboard the vehicle. If message m containing information for S distinct segments with IDs $i_1, \ldots, i_S$ is received at node n, the tuples $(s_{n,k}, t_{n,k})$ are updated based on the time stamps

$$s_{n,k} \leftarrow \begin{cases} s_{m,k}, & \text{if } t_{m,k} > t_{n,k} \\ s_{n,k}, & \text{otherwise} \end{cases}$$
$$t_{n,k} \leftarrow \max(t_{m,k}, t_{n,k}), \quad k = i_1, \ldots, i_S. \tag{2}$$

Here, $s_{m,k}$ and $s_{n,k}$ are the information values for segment with ID k in the message and at the node, respectively, and $t_{m,k}$, $t_{n,k}$ are the corresponding time stamps.

The application recurrently sends broadcast packets with (parts) of its current information on all relevant segments in the local area. More important segments are included more often.

[5]Depending on the type of data being distributed, a node can also be a roadside unit, e.g., gas station, injecting data into the network.

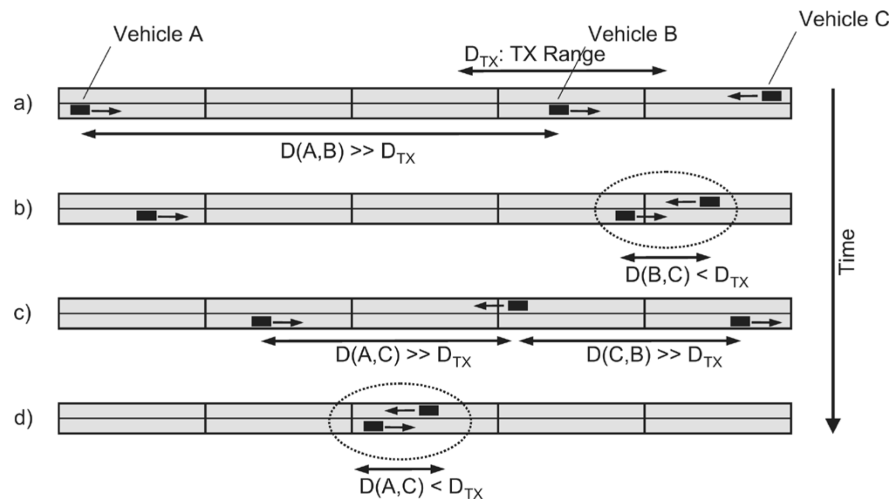


Fig. 3. Information dissemination in cases of low penetration.

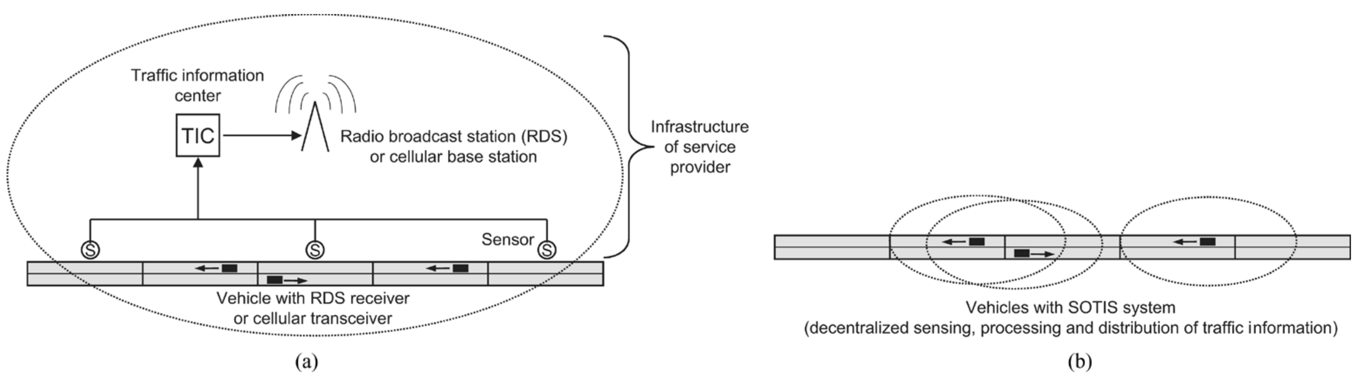


Fig. 4. Comparison of the conventional form of traffic information systems with the proposed SOTIS. (a) Conventional centralized traffic information system. (b) Decentralized self-organizing traffic information system.

The effect of this communication paradigm is shown in Fig. 3, which illustrates the communication in situations with a low density of equipped cars: In Fig. 3(a), Vehicle A and Vehicle B are driving in the same direction. Vehicle B senses the conditions ahead of Vehicle A, but since the distance $D(A,B)$ between the two vehicles is much larger than the transmission range D_{TX}, they cannot communicate directly. Later, in Fig. 3(b), Vehicle C on the opposite lane is in the transmission range of Vehicle B. It receives and stores the broadcasted per-segment data. In Fig. 3(c), the vehicles travel for a while without any communication partner in range. Finally, in Fig. 3(d), Vehicle A can receive the information from Vehicle B although both vehicles were never in (single- or multihop!) communication range.

IV. SOTIS

A SOTIS based on IVC is a typical application in which the SODAD method can be applied to create a scalable intervehicle information system, which requires only a low penetration ($\approx$1%–3%). This section introduces the SOTIS example, which will be evaluated by simulation and prototypic implementation afterward.

A. Motivation and Basic Idea

Conventional traffic-information systems (TIS) are organized in a centralistic way, as illustrated in Fig. 4(a): Sensor-based traffic-monitoring systems deployed directly at the roadside collect information about the current traffic conditions. This data is transferred to a central traffic-information center (TIC), where the current road situation is analyzed. The result of this situation analysis is packed into messages for the Traffic Message Channel (TMC),[6] forwarded to the FM radio broadcast station and transmitted via RDS to the driver. Alternatively, the traffic messages can be transferred on demand via cellular mobile phone network.

A centralized service for distributing traffic information has several technical disadvantages.

- A large number of sensors need to be deployed since the service is limited to streets where sensors are integrated. Thus, a large investment for the communication infrastructure (sensors, central unit, wired and wireless connections) is necessary.
- The recorded traffic density data is transmitted for traffic analysis to a central unit (TIC). This procedure

[6]The TMC is an application of the FM radio data system (RDS) for broadcasting traffic information.

causes a relatively high delay (typically 20–50 min) before the result is broadcast to the drivers.

- Since a central unit covers a relatively large area and due to the limited bandwidth,[7] for transmitting the traffic messages only major events are transmitted. A constantly updated and detailed information for the local area is not available.
- In the case of cellular distribution of traffic information, service charges will apply.

For these reasons, an alternative and completely different approach for monitoring the traffic situation and distributing the traffic messages to vehicle drivers is proposed, based on the SODAD method presented in Section III. A decentralized self-organizing traffic information system is designed by combining a digital map, a positioning system (e.g., GPS) and wireless *ad hoc* communication among the vehicles. Since the first two components are already available in modern vehicles equipped with navigation systems, the only additional requirement is a wireless interface for IVC. In this decentralized SOTIS, vehicles inform each other of the local traffic situation by IVC, as illustrated in Fig. 4(b). The traffic situation analysis is performed locally in each individual car. No communication/sensor infrastructure is required. For a global route optimization, the SOTIS information for the local area (e.g., for a radius of 50–100 km) can be combined with traffic information provided by roadside access points or conventional centralized systems.

B. Application of SODAD

SOTIS is a typical case where the application of SODAD is advantageous (see Section III-A). For each road segment that a vehicle drives, it records the observed average velocity. The aggregation function $a(\cdot)$ is defined in a way that the data value $s_{n,i}$ for a segment i at node n is the mean of the vehicle's own velocity d_1 and that of all K other vehicles in the transmission range

$$s_{n,i} = a(d_1, d_2, \ldots, d_{K+1}) = \frac{1}{K+1} \sum_{k=1}^{K+1} d_k, \qquad K \in \mathbb{N} \cup 0. \tag{3}$$

The time stamp $t_{n,i}$ is set to the time of data aggregation. For node n, the tuple $(s_{n,i}, t_{n,i})$ sufficiently characterizes the current traffic situation in segment i, since the road type is also known. Within the system, this per-segment information is distributed using the technique known from Section III-B. Each vehicle obtains traffic information for all road segments in the local area. This information can either be displayed to the driver (e.g., by coloring the roads displayed in the navigation system according to their traffic conditions) or is used for calculating the best (i.e., fastest) traffic route for the current situation.

C. SOTIS System Structure

Fig. 5 illustrates the functional structure of SOTIS: Traffic information in the form of tuples $(s_{n,k}, t_{n,k})$ is collected in the knowledge base. It contains the traffic information for all segments in the local area (e.g., in a range of 200 km). Information is discarded if it has become outdated or the capacity of the knowledge base is reached. Using the information stored in the knowledge base, a traffic analysis is continuously calculated in each car. This analysis determines which information is to be included in the next broadcast data packet (examples for selection criteria are presented in Section VII). By adapting the rate for generating these recurrent broadcast packets to the local conditions,[8] overload situations are avoided.

[7]In case of the TMC, the data rate for sending traffic messages is limited to 37 bits/s.

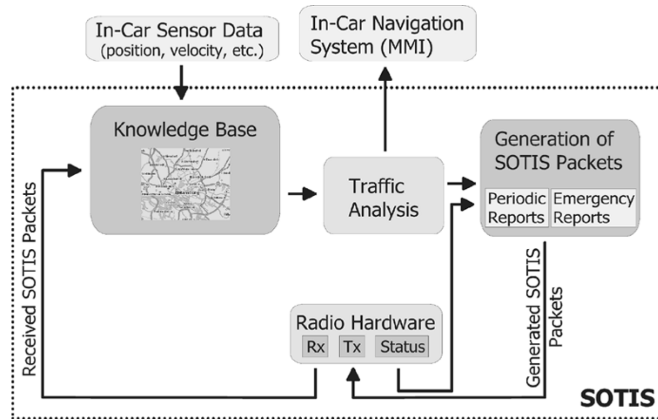


Fig. 5. SOTIS system implemented in each vehicle.

TABLE I
PARAMETERS USED IN THE TRAFFIC SIMULATION

Total road length	250 km
Number of lanes	2 per direction
Deceleration prob.	0.4
Constitution of traffic	15 % slow, 85 % regular vehicles
Desired velocity	108 km/h (slow), 142 km/h (regular)
Traffic density	7.5 veh./lane/km, 10 veh./lane/km, 15 veh./lane/km
Mean Velocity	95.6 km/h, 101.3 km/h, 106.4 km/h

V. PERFORMANCE EVALUATION OF SOTIS

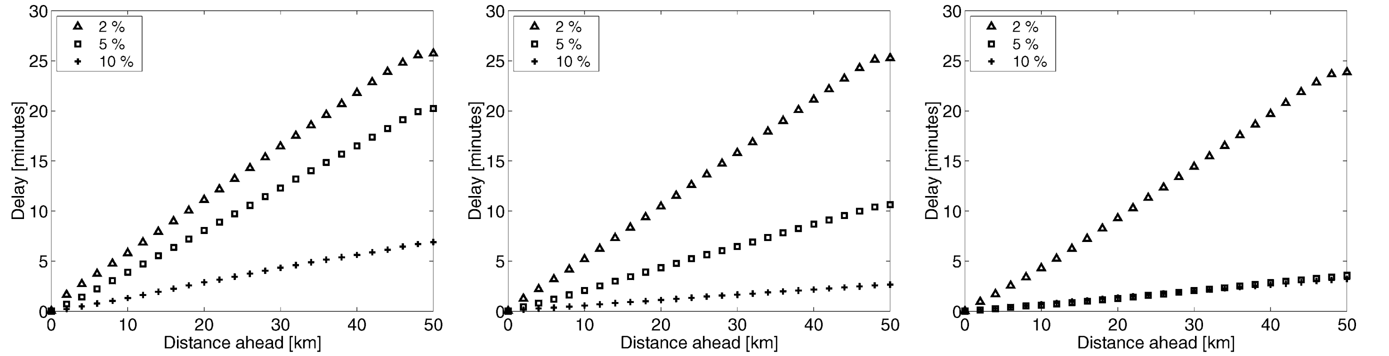
In order to evaluate the performance of SOTIS, a simplified model has been developed that was implemented within the network simulator[9] *ns-2*. The simulation and system parameters as well as modifications and extensions of the simulator are outlined in the following section.

A. Road-Traffic Simulation and Parameters

For simulation, the road traffic and movement of individual nodes (cars) must be described by a mathematical model. In this respect, the typical movement pattern in an intervehicle *ad hoc* network is very different as compared to a general *ad hoc* wireless network simulation (where schemes such as the "random walk" model can be used to simulate node movement). Therefore, the ns-2 simulator has been extended with a movement

[8]This aspect is covered in more detail in Section VI. Until this point, a non-adaptive system is assumed.

[9][Online]. Available: http://www.isi.edu/nsnam/ns/



(a) (b) (c)

Fig. 6. Performance of the basic SOTIS system for a penetration of 2%, 5%, and 10% when the traffic density is varied. (a) Low traffic density (7.5 vehicles/lane/km). (b) Medium traffic density (10.0 vehicles/lane/km). (c) High traffic density (15.0 vehicles/lane/km).

model based on a microscopic traffic simulation using a cellular automaton approach [10]. It also allows passing, if safety conditions are not violated [11]. The scenario presented in this paper simulates a typical highway situation with two lanes per direction.

Table I lists the parameters used for road-traffic simulation. Arrival times are assumed to be Poisson distributed; initial time gaps between adjacent vehicles are, therefore, chosen from an exponential distribution.

B. Communication Parameters

The focus of this paper is on techniques for information dissemination, not on details of the physical or link layer. Therefore, the link layer used for the performance evaluation is a standard IEEE 802.11 system with a data rate of 1 Mbit/s. It has to be noted that the proposed methods do not require a specific wireless transmission technology. IEEE 802.11 was chosen for the simulations since it is well known and similar to DSRC [4]. However, IEEE 802.11 is known to have severe limitations—an air interface specifically developed for the vehicular environment will usually result in a better performance, i.e., IEEE 802.11 can be regarded as a worst-case scenario.

The usual ns-2 two-way ground propagation model is used and packet collisions are detected. All packets are transmitted as broadcast. The transmit frequency is set to 2.472 GHz and transmit power is 15 dBm. The receive threshold is adapted in order to achieve a communication range of 1000 m, since this is the expected range of air interfaces developed for IVC, e.g., DSRC [4] or UMTS Terrestrial Radio Access Time-Division Duplex Ad Hoc (UTRA TDD *Ad Hoc*). [12]. Omnidirectional antennas at a height of 1.5 m are assumed.

A resolution of 500 m is assumed to be sufficient for traffic information. For simplicity, a constant segment size of 500 m is used. Each SOTIS-equipped vehicle transmits two broadcast packets per second. Of these packets, 66% include traffic information for the road on which the vehicle is traveling and the remaining packets are reserved for transmitting information for other roads. For evaluating the system performance, the information stored in the knowledge base of each car is analyzed every 500 ms of simulated time and the respective delay with which each information element has been received is calculated.

For each of the three simulated traffic densities, the performance is evaluated if 2%, 5%, and 10% of all vehicles are equipped.

C. Simulation Results

The main objective of the simulations was to evaluate if the SOTIS technology can provide traffic information with a reasonable delay. In Fig. 6(b), results from a typical scenario with a traffic density of 10 vehicles/lane/km are shown. The average delay of information about a specific road segment increases linearly with its distance from the current position. For a situation in which 10% of all vehicles are equipped with SOTIS technology, the information delay is small (≈ 3.5 s/km). Even if only 2% of all vehicles are equipped, information is successfully distributed. In this case, the delay increases to ≈ 31.4 s/km, which is still acceptable for comfort applications such as SOTIS, given the relatively large time scale on which traffic conditions usually change. A state-of-the-art conventional TIS with an average delay of 20 min would be outperformed for a local area of ≈ 340 km for 10% penetration and an area of ≈ 40 km for only 2% penetration.

Fig. 6(a) and (c) illustrates the effect of lower and higher traffic density on the delay. In the case of a low traffic density, the delays for a market penetration of 5% and 10% increase significantly. This is due to the fact that the chance for a communication partner in transmission range decreases; therefore, the information is less often forwarded using the air interface—the share of transport onboard vehicles increases. For very low penetration, this method of transport is already dominating, the delay increases only slightly. A similar effect occurs for high traffic densities. In this case, the delay for scenarios assuming a high SOTIS penetration is mainly caused by the time between two consecutive broadcast transmissions; thus, it is only slightly reduced with a higher traffic density.[10]

The performance results in these road scenarios demonstrate that the system is able to provide information for the local area of the vehicle even if only a low penetration of 2%–3% is assumed. Compared to conventional multihop communication, much larger ranges in which information is distributed can

[10]Another contrary effect in the case of high traffic densities is that the average velocity of a vehicle decreases (by approximately 10% as compared to a low density for the simulated scenarios).

TABLE II
EXAMPLES FOR PROVOKING AND MOLLIFYING EVENTS IN THE PROVOKED BROADCAST SCHEME

Examples for Provocations

Event	**Intention**
Reception of information being out-of-date	Transmitting vehicle needs updated information
Reception of packet with significantly different new information	Favor propagation of changes
Reception of information from vehicle with large distance	Favor large hops in propagation
Indication (e.g. by lower layers) of excessive bandwidth	Decrease delay of information propagation

Examples for Mollifications

Event	**Intention**
Reception of similar/more up-to-date information from nearby	Avoid redundant transmissions
Indication that number of received reports exceeds threshold	Limit maximum used bandwidth

be achieved, e.g., for a comfort application such as SOTIS, where an average delay of up to 30 min for marginal segments is acceptable, an information range of more than 50 km is possible even in cases of low penetration.

VI. ADAPTIVE BROADCAST

Until now, the considered basic broadcast scheme was static: Broadcast messages were generated at constant intervals and the transmission range/transmission power of the vehicle was assumed to be fixed. Overload conditions were not actively avoided—their effect was simply mitigated by the high level of redundancy due to the periodic repetition of the broadcast messages. This basic system is now extended with a heuristic approach for the dynamic adaptation of the broadcast interval in order to actively avoid overload conditions and to favor the propagation of significant changes.

A. Challenges and Requirements

Adaptive information dissemination in the considered vehicular *ad hoc* network is a challenging task: The environment is highly dynamic (relative velocities of up to 400 km/h) and the density of vehicles can vary from one to two vehicles per kilometer in low density night traffic to more than 100 vehicles/km/lane in traffic-jam situations. These node densities can change completely within seconds, e.g., at an intersection of an empty and a crowded highway.

Whereas in low-density situations a large transmission range is advantageous, in high-density situations it leads to a decrease of the available transmission bandwidth for an individual vehicle. Analogously, in low-density situations, a short intertransmission interval is beneficial, but can lead to overload conditions in situations of high density. Basically, the following methods could be used to solve this problem: adaptation of the transmission range (power control), adaptation of the intertransmission interval, and combined approaches. In this paper, the focus is on the adaptation of the intertransmission interval, since, in a typical highway situation, information is forwarded along a line and, in this case, power control does not lead to a spatial reuse gain.

The performance of a broadcast scheme can be characterized by the combination of two properties: required bandwidth (mean rate) and average deviation of information available in a vehicle compared to the actual value of a segment. This average deviation (i.e., mean error) will usually depend on the distance of a segment.

B. Adaptation Procedure

The heuristic approach for the adaptation of the transmission interval, called *provoked broadcast* in the following, adapts the intertransmission interval to the local environment and knowledge gained from received packets in order to: 1) reduce the delay with which information is propagated; 2) favor the propagation of significant changes; 3) avoid redundant transmissions; and 4) occupy less bandwidth in cases of congestion.

The basic idea is the following. A default intertransmission interval T_{upd} small enough to recognize a vehicle passing by at the maximum relative velocity is chosen. If a maximum relative velocity of 500 km/h and a transmission range of 1000 m is assumed, an interval of 5 s is sufficient. This default interval is adapted according to two kinds of observed events:

1) **Provocation:** A *provocation* is an observed event that reduces the time that elapses until the next broadcast packet is transmitted.
2) **Mollification:** A *mollification* is an observed event that increases the time that elapses until the next broadcast packet is transmitted.

Examples for provoking and mollifying events, which will also be used for simulations (Section VI-H), are listed in Table II.

C. Parameters of Adaptive Broadcast

Upon the reception of a data packet, its content is examined in order to update the vehicle's knowledge base (SODAD). Furthermore, it is determined if a provoking or mollifying event has occurred: Based on the comparison of the received data and its time stamp within the knowledge base for each individual road segment, a weight $w_{m,n}$ of a received message m at node n is calculated. It indicates the discrepancy of the received per-segment data compared to the node's previous knowledge. The decision if an information value is significantly newer or different than the previously available information is based on two threshold values: If the difference of the two time-stamps exceeds the threshold ΔT_{th}, $w_{m,n}$ is increased by a constant q_{date} (the so-called date quantum). Analogously, if the difference of the two information values exceeds the threshold ΔI_{th}, $w_{m,n}$ is increased by q_{info}.

Thus, the weight of a received message composed of information values for S distinct segments with IDs $i_1, \ldots, i_S$ is calculated as

$$w_{m,n} = \sum_{k=i_1,\ldots,i_S} w_{\text{info}}(s_{m,k}, s_{n,k}) + w_{\text{date}}(t_{m,k}, t_{n,k}) \quad (4)$$

where

$$w_{\text{info}}(s_{m,k}, s_{n,k}) = \begin{cases} q_{\text{info}}, & |s_{m,k} - s_{n,k}| \geq \Delta I_{\text{th}} \\ 0, & |s_{m,k} - s_{n,k}| < \Delta I_{\text{th}} \end{cases}$$
$$w_{\text{date}}(t_{m,k}, t_{n,k}) = \begin{cases} q_{\text{date}}, & |t_{m,k} - t_{n,k}| \geq \Delta T_{\text{th}} \\ 0, & |t_{m,k} - t_{n,k}| < \Delta T_{\text{th}}. \end{cases} \quad (5)$$

Again, the values $t_{m,k}$ indicate the time stamp for segment k in message m and $t_{n,k}$ the time stamp for segment k in the knowledge base of node n. Analogously, $s_{m,k}$ and $s_{n,k}$ are the respective information values for segment k.

A message will be assigned a high weight $w_{m,n}$ if it was transmitted by a node that has significantly different information for the respective segments. In contrast, a low weight means that the node that broadcast this message has a very similar view of these segments. In the following, it is assumed that the constants q_{info} and q_{date} are chosen in a way that $S \cdot (q_{\text{info}} + q_{\text{date}}) \leq 1$ and, therefore, the weight of a message is in the interval $[0, 1]$.

D. Provoking and Mollifying

Based on the weight of a received message, a node determines if a provocation or mollification has occurred. Reception of a message with a weight less than the mollification weight w_{mol} causes an increase of the remaining time by Δt_{mol} until the next transmission of a traffic analysis for the respective road segments and reception of a message with a weight larger than the provocation weight w_{prov} decreases this time by Δt_{prov}. Both values can either be chosen as absolute times or relative to the currently remaining time until the next transmission. In general, the grade in which the current interval is adapted should correspond to the weight, e.g., a high weight (≈ 1) should cause a more significant adaptation of the interval than a weight just slightly larger than w_{prov}. A detailed explanation of the parameters used is given in Section VI-H.

E. Interdependence of Provoking and Mollifying

Boundary condition for the outlined self-organizing system is that the bandwidth is limited. One approach is to use the event that the desired network load is exceeded as a mollification. However, in many cases, this is not necessary due to the interdependence of provoking and mollifying events outlined in the following example. Consider a cluster consisting of M individual nodes, which are all in transmission range of each other. Since they are at a similar physical location, they will have a similar view of the surrounding environment. Now, an approaching node transmits a data packet with significantly new information. The weight computed in each of the receiving nodes will, therefore, be high and all will reduce the remaining time until their next transmission. However, since the nodes are not synchronized, one of them will transmit first. When the $(M-1)$ other nodes receive this data packet, a low weight is assigned (since all have similar information) and a mollification is caused. Therefore, the provocation caused by the approaching node causes only one transmission immediately after the reception. An interesting question—which will be considered next—is, which of the M nodes in the cluster should perform this transmission?

TABLE III
PARAMETERS FOR THE ADAPTIVE BROADCAST SCHEME

Param.	PBcast Set 1	PBcast Set 2	PBcast Set 3	PBcast Set 4	PBcast Set 5
q_{info}	0.005	0.010	0.020	0.001	0.040
q_{date}	0.005	0.005	0.000	0.001	0.005
ΔT_{th}	60 s				
ΔI_{th}	10				5
ΔD_{th}	750 m				
w_{prov}	0.04				
w_{mol}	0.01				
$T_{Ichange}$	300 s				

F. Influence of Distance

In a self-organizing network based on broadcast messages, it is common sense that favoring large hops in the propagation of information can be used to reduce the required bandwidth. Furthermore, nodes at a larger distance are more likely to be out of transmission range in the near future. Therefore, a distance quantum q_{dist} is calculated, depending on the distance d_{tx} to the transmitting node

$$q_{\text{dist}}(d_{\text{tx}}) = \begin{cases} 0, & d_{\text{tx}} < D_{\text{th}} \\ \frac{d_{\text{tx}}}{d_{\text{tx,max}}}, & d_{\text{tx}} \geq D_{\text{th}} \end{cases} \quad (6)$$

where $d_{\text{tx,max}}$ is the maximum transmission range, d_{tx} is the distance of the node that transmitted the message (calculated using position information in the packet header), and D_{th} is a threshold. If $q_{\text{dist}} > 0$, a provocation is caused. Therefore, more distant nodes are more likely to transmit next. Since their transmissions will cause mollifying events for the other nodes in transmission range, large hops are favored in the propagation of information.[11]

G. Potential Risks

A potential disadvantage of the proposed scheme is that, in cases where a strong provocation (i.e., reception of a packet with $w \approx 1$) occurs within a cluster of nodes, the nodes will collectively reduce their remaining time until the next transmission. This can increase the data packet collision rate slightly. However, a suitable medium-access control (MAC) protocol (e.g., reservation based) can be used to avoid this risk and, furthermore, our simulations indicate that even if the scheme is used on top of a standard 802.11 MAC, the rate of collisions is low.

H. Performance Evaluation

For performance evaluation, a simulation of the vehicular *ad hoc* network analogous to Section V was conducted. The same road traffic model and parameters (Table I) were used, except for a reduction of the simulated road length to 68 km in order to

[11] A similar approach is the basis of the recently proposed beaconless or contention-based geographic routing algorithms [8], [13].

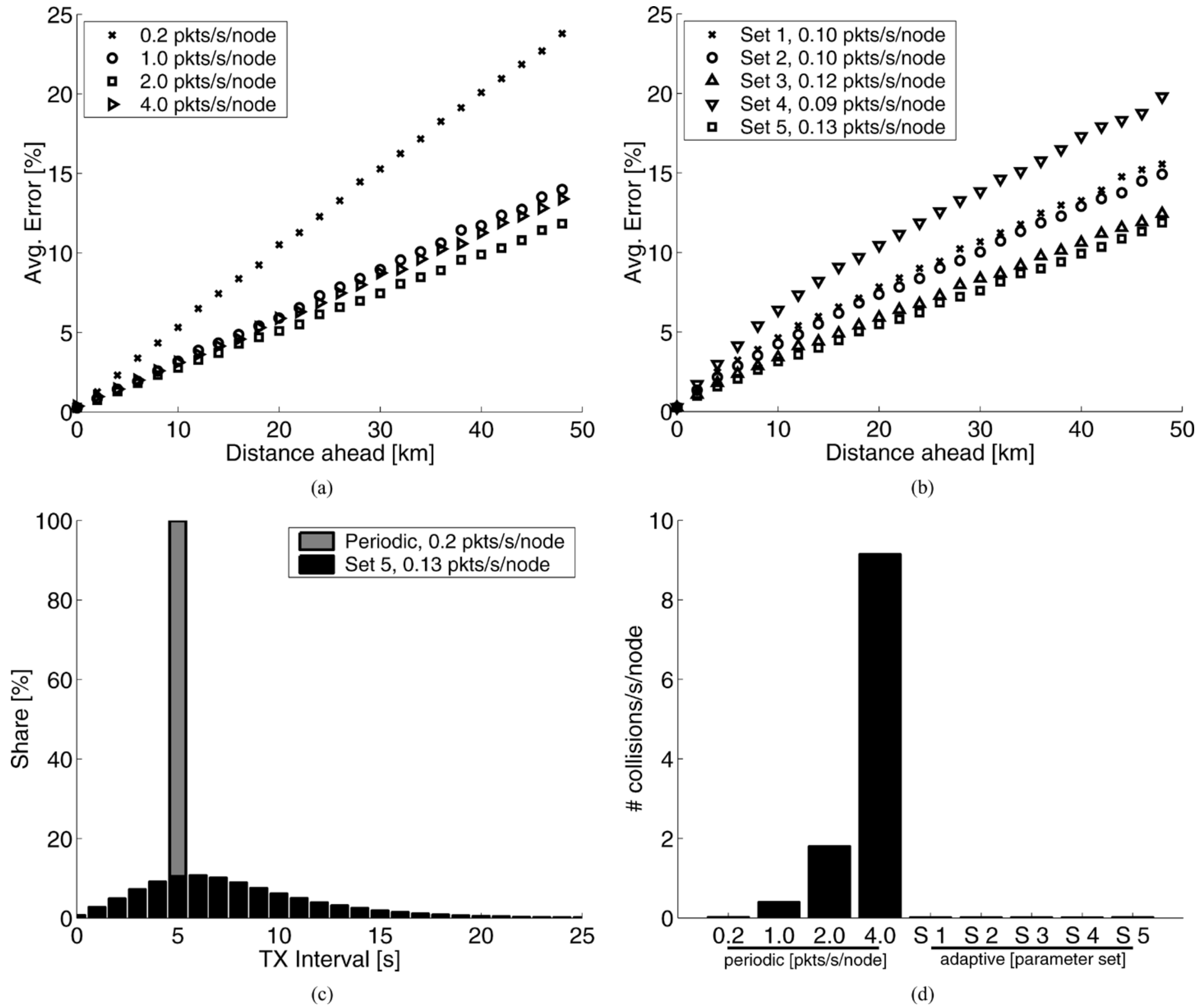


Fig. 7. Performance comparison of the adaptive scheme with a periodic broadcast: average error of available information, transmission intervals, and collisions. (a) Average error for periodic broadcast. (b) Average error for adaptive broadcast. (c) and (d) Packet collisions.

limit the simulation time. For all scenarios, a penetration rate of 10% and a traffic density of 10 vehicles/lane/km was assumed. As a result, the total number of vehicles simulated was ≈ 5800 vehicles. Per scenario, 8000 s of simulation time were simulated; the last 6000 s were used for calculating the statistics.

Table III describes the different parameter sets that were used for the system parameters introduced in Section VI-C: the main parameters varied over the five sets are the info quantum q_{info} and the date quantum q_{date}. In combination with the threshold values ΔI_{th}, ΔT_{th} and the weights w_{prov} and w_{mol}, these determine how fast the adaptation is performed.

The values for Δt_{prov} and Δt_{mol} by which the currently remaining time t until the next packet transmission is adapted (Section VI-B) are calculated as follows. In case of a mollification, the remaining time until the next transmission is increased by 1 s; in the case of a provocation, the remaining time is multiplied by $(1 - q_{\text{dist}})(0.5 + w)$. The required bandwidth for the adaptive broadcast scheme depends on the data to be distributed. In order to have a worst-case estimate, a uniform distribution of the per-segment information values was assumed (maximizes entropy). Information values were updated independently and randomly for each segment with the change period T_{Ichange}. In reality, the information values will most likely have less entropy due to the spatial component of the distributed information and appropriate coding techniques could significantly reduce the amount of data to be transferred. These aspects are out of the scope of this paper.

Four periodic and five adaptive scenarios have been simulated. For the periodic scenarios, the data rate of each node was varied from 0.2 to 4.0 packets per second per node. Fig. 7(a) shows that increasing the rate from 0.2 to 1.0 packets/s/node significantly improves the available information, whereas a further increase results in only a minor improvement. For 4.0 packets/s/node the accuracy of the information available even decreases. The reason is that in constellations with high node densities, too many packets are lost due to collisions [see Fig. 7(d)].

For the adaptive broadcast scheme [Fig. 7(b)], the first important observation is that the performance of the periodic scheme can be achieved with about one-tenth of the required bandwidth, e.g., comparing the adaptive scheme with parameter set 1, 0.1

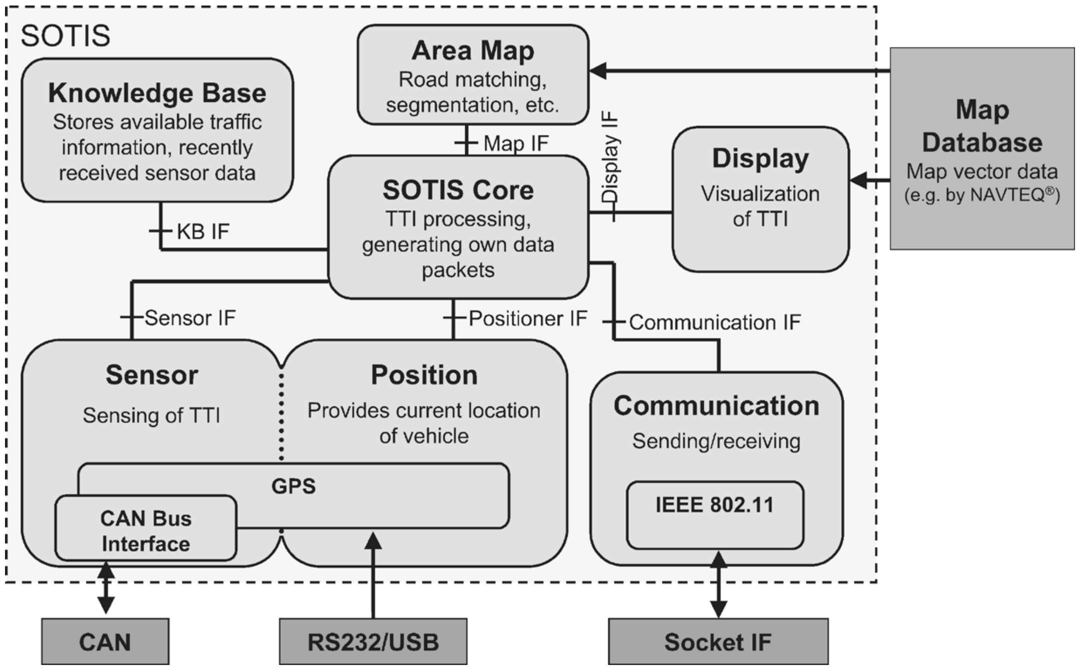


Fig. 8. Block diagram of the SOTIS prototype.

packets/s/node, to the periodic scheme with 1.0 packets/s/node. More "aggressive" parameter sets, e.g., Set 5, increase the accuracy of the available information, but also require some additional bandwidth. The superior performance of the adaptive scheme is explained by Fig. 7(c) and (d): The number of collisions is reduced and the transmission interval is adapted to the current situation and available information of a vehicle. The indicated performance improvement clearly compensates the additional computational overhead introduced by the adaptive scheme.

VII. SOTIS Prototype

For the prototype implementation, the main motivation is to demonstrate the feasibility and features of a self-organizing traffic information system—for small scenarios, the validation of simulation results is also possible.

A. Components

The functionality of SOTIS is realized by the seven individual components illustrated in Fig. 8.

1) *SOTIS core* coordinates the processing of traffic information and the composition of new data packets. Data is acquired using the three "lower" interfaces to sensor, position, and communication components.
2) *Knowledge base* stores the per-segment information available at each vehicle, indexed by the road identifier.[12] It periodically evaluates the importance of each segment and discards information of low relevance, e.g., if the segment time stamp is outdated. The knowledge base also tracks the last time that a segment has been transmitted.
3) *Area map*. The main functions offered by the *area map* component are map matching and segmentation. Geographical coordinates can be converted to the triple (road identifier, segment number, and direction) and *vice versa*. Map information can either be obtained from a commercial vector map[13] or a proprietary map format (combination of bitmap images and vector data).
4) *Display*. Visualization of the currently available information, the local area of the vehicle, and all vehicles in direct communication range. Depending on the available information on the average velocity and the road type of a segment, traffic conditions are visualized by the color of a road segment: red indicates very low, yellow medium, and green high speeds (relative to speed limit for the respective road type).
5) *Position* provides information on the current location of the vehicle—updated once per second—using a commercial GPS receiver. (In combination with map matching, GPS accuracy proved to be sufficient in our tests, but could be increased further by using onboard information, e.g., via Controller Area Network (CAN) interface.)
6) *Sensor* determines the traffic information for the current location of the vehicle. For the prototype, information on the average velocity of a vehicle in a segment is used, obtained via GPS and/or CAN.
7) *Communication*. Although the IEEE 802.11 standard has problems in vehicular (city) scenarios [12], it is used in the SOTIS prototype simply because no other more suitable transceiver was available at a comparable cost. Commercial IEEE 802.11b wireless local area network (LAN) cards are used (DSSS, 1 Mbit/s mode).

[12]In total, less than 20 B per segment are required.

[13]Currently, *NAVTEQ* maps via *Mapsolute* are supported.

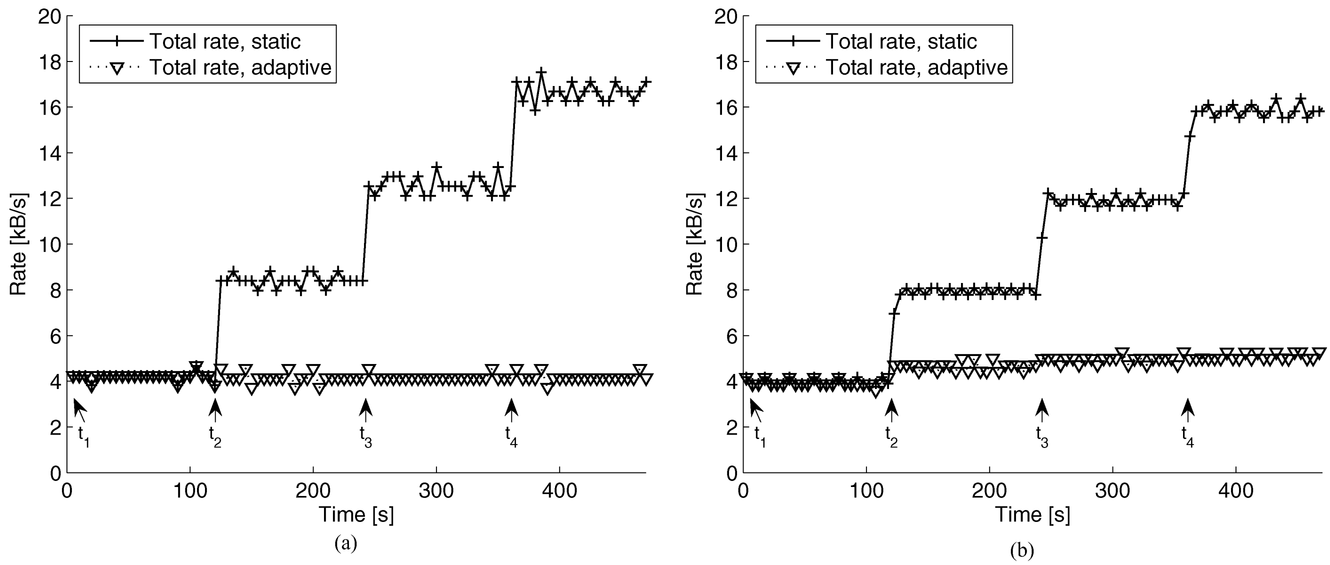


Fig. 9. Comparison of simulation and measurement for the test scenario. (a) Simulation results (ns-2). (b) Measurement results (prototype).

B. Test Results

Typical scenarios have been successfully tested with the prototype system in various parts of northern and central Germany: Gathering traffic information in each vehicle, information dissemination in a line of vehicles, and information dissemination onboard a vehicle on the opposite lane.

Furthermore, a specific scenario involving four prototype nodes has been evaluated: The four vehicles are located close to each other (total connectivity). At the beginning, all nodes are switched off. Then, the nodes are activated consecutively. At time $t_1 = 0$ s, Node 1 starts sending, at $t_2 = 120$ s Node 2, at $t_3 = 240$ s Node 3, and at $t_4 = 360$ s Node 4. Thus, although no movement is present, the scenario imitates a dynamically increasing group of vehicles equipped with the system. At each node, the rates of transmitted and received data packets are measured. The prototype is tested in two configurations.

- **Static broadcast interval:** As assumed in Section V, nodes are transmitting with a static intertransmission interval. One User Datagram Protocol (UDP) packet is sent every 350 ms.
- **Adaptive broadcast interval:** The intertransmission interval is adapted using the adaptive mechanism outlined in Section VI. Parameters for the adaptation are the same as in Table III and the default interval is set to 350 ms.

For both configurations, UDP payload size is 1400 B. The same scenario with both configurations was also evaluated by network simulation.

Fig. 9 compares the results of the simulations with the prototype measurements. For both cases (static and adaptive interval), the total data rate observed at a node (sum of received and transmitted rates) is plotted over time. The symbol t_i indicates the time at which Node i is activated. For the static interval, the data rate increases linearly with the number of active nodes. If the adaptive system is used, the total data rate does not increase significantly if a new node at a similar same location is activated. The nodes have a similar view on the local environment and the observation of the transmissions of identical data by other nodes causes an adaptive increase of the transmission interval.

In general, the measurement results are in good accordance with the simulations. In Fig. 9(b), a slight increase of the total rate is observed at t_2 for the adaptive system, which does not occur in the simulations. A possible explanation is that the additional delay for processing the data packets in the network protocol stack/application in combination with the short default interval causes data packets to be transmitted that can be suppressed in the simulations.

VIII. Conclusion

IVC can significantly increase passenger safety and comfort. However, the network characteristics in the vehicular environment are a real challenge for designing suitable air interfaces, protocols, and applications. A critical requirement for market introduction is that the system offers significant benefit even if only a low ratio of all vehicles is equipped.

The main contribution of this paper is threefold. First, a novel method for data abstraction and dissemination in vehicular *ad hoc* networks is proposed. It is targeted at the dissemination of data with a spatial component in sparsely connected mobile ad hoc networks. An additional heuristic approach for the adaptation of the intertransmission interval reduces the required bandwidth significantly. Second, this method is applied in a SOTIS for the distribution of detailed and up-to-date travel and traffic information for the local environment of a vehicle. Performance evaluation by the means of simulation shows that SOTIS requires only a very low penetration ($\approx 1\,\% - 3\,\%$). Third, an experimental prototype is presented. Based on off-the-shelf hardware, it demonstrates the feasibility of the proposed system. Early measurement results are in good accordance with the simulation results.

APPENDIX
EXPECTED VALUE OF THE MULTIHOP RANGE

To obtain an analytic approximation of the average multihop range, i.e., the average range in which an *ad hoc* routing protocol could possibly disseminate information, results from the theory of coverage processes [14] are applied to the considered multihop scenario: On an individual street, sections in which vehicles can communicate using multihop communications (*clumps* in the theory of coverage processes) alternate with sections not covered by any wireless air interface (*spacings*). For this spatial alternating renewal process, clumps are formed by a superposition of individual segments of length R, where R is the transmission range of the air interface. The expected value of the clump length C corresponds to the average range in which multihop communication is possible.

For a fixed length R, the expected clump length C is given by [14]

$$E\{C\} = \frac{e^{R\lambda} - 1}{\lambda}. \tag{7}$$

For calculating the intensity λ, we assume a constant traffic-flow volume q per lane and that all vehicles travel with a fixed velocity v. Furthermore, an exponentially distributed headway is assumed. In this case, the parameter λ is

$$\lambda = 2N\gamma\frac{q}{v} \tag{8}$$

where γ (with $\gamma \in [0, 1]$) denotes the assumed penetration of the *ad hoc* system and N the number of lanes per direction. This analytic approximation of the average multihop range was verified by simulations.

ACKNOWLEDGMENT

The authors would like to thank M. Lott and R. Halfmann of Siemens AG, Munich, Germany, for fruitful discussions during the FleetNet project and the companies *NAVTEQ* and *Mapsolute* for providing the digital map data.

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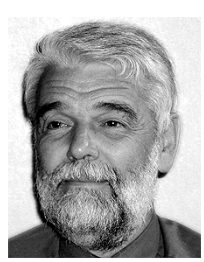

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