IVC in Cities: Signal Attenuation by Buildings and How Parked Cars Can Improve the Situation

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Abstract—We study the effectiveness of Inter-Vehicle Communication (IVC) in urban and suburban environments at low node densities, with a particular focus on cooperative awareness and traffic safety. The recently standardized DSRC/WAVE protocol suite defines a platform for such applications, which mainly focus on beaconing, i.e., periodic 1-hop-broadcast. In general, such safety relevant transmissions are defined by time criticality. One of the major problems to be solved is how to tackle the very difficult and complex radio signal attenuation due to buildings and other obstacles, especially in cities. Typical concepts address this problem by requiring all vehicles to also act as relays or by using dedicated Roadside Units (RSUs). We show how such systems may be operated more efficiently and how the situation can be further improved by relying on parked vehicles in addition to, or as a replacement for, RSUs. Given the fact that the US DOT is already evaluating whether to make DSRC mandatory for new cars, wide availability of radio equipped cars can be predicted; also the impact in terms of energy consumption is negligible. We performed an extensive set of simulations to evaluate the negative impact of buildings at low node densities and the benefit of our proposal. Our results clearly indicate that situation awareness can be significantly improved. When disseminating safety critical events in a realistic scenario, reasonable numbers of parked cars can increase cooperative awareness by up to 25 %, a factor which requires an unreasonably costly number of RSUs. To the best of our knowledge, we are the first to propose the utilization of parked vehicles as relay nodes for safety applications in vehicular networks.

Index Terms—Inter-Vehicle Communication, Vehicular Ad Hoc Network, Parked Vehicles, Roadside Unit, Road Safety Applications

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1 Introduction

In 2009 the European Transport Safety Council reported over 1.3 million traffic accidents in the European Union with a total of approximately 36 000 citizens killed. Efforts to reduce accidents and casualties include the design of safer vehicles and roads, both of which will likely also rely on Inter-Vehicle Communication (IVC), i.e., cars forming a vehicular network [1]. Currently, a Dedicated Short-Range Communication (DSRC) IEEE 802.11p stack [2] for wireless communication in vehicular networks is being standardized. Vehicles are envisioned to periodically broadcast beacon messages including their current state (information such as speed, position, and heading) to all nodes in their vicinity to inform them about their presence. In Europe these beacons are called Cooperative Awareness Messages (CAMs), in the U.S. they are referred to as Basic Safety Messages (BSMs).

Safety applications demand extremely low transmission latency [3]. For some applications it is required to reach as many neighboring vehicles as possible in due time [1], [4]. When relied upon, late or missing information (caused, e.g., by lost messages) may lead to severe accidents. Cooperative communication mechanisms are needed to avoid such accidents including possible fatalities.

Discussing the complete information processing chain of collision avoidance systems is out of the scope of this paper. Instead, we focus on the message transmission. Current studies of collision avoidance systems commonly assume DSRC transmission delays of 25 ms and 300 ms in normal and poorer conditions, respectively [5]. However, there are several reasons why such message transmissions might fail. First, antennas commonly have directionality characteristics and will not emit the signal in all directions with uniform strength [6]. Secondly, a signal can be interfered with by another signal, rendering it undecodable. Finally, and mostly importantly in urban and suburban environments, radio propagation effects can significantly reduce the range of radio transmissions.

In this paper, we concentrate on this third aspect, and particularly on signal loss due to shadowing caused by obstacles in urban and suburban environments [7]. In metropolitan areas the line of sight between vehicles is often blocked by obstacles such as buildings, vegetation, or parked and moving vehicles [8], [9]. This does not necessarily result in packet loss but still leads to a considerable attenuation of the signal. Depending on the material of the obstacle, the theoretical transmission range of a node will then not be reached [7]. Other nodes – although within this range – may not sense emitted beacons of a node until both nodes move closer to each other. The time it takes for both nodes to get into actual communication range constitutes an additional delay that can reduce the benefit of safety applications.

Especially in urban scenarios, buildings and other obstacles may block the transmission between two vehicles

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The manuscript is based on earlier work on using parked vehicles to bridge communication gaps that was presented at IEEE GLOBECOM.

with high probability. The best example is an intersection, where warning systems could be shown to be able to drastically reduce the number of accidents [10], [11]. However, when cars are approaching this intersection, direct connectivity might not be possible [12]. Another example is emergency breaking [13]. Again, direct line of sight connectivity might not be granted, for example because of a curve. In all these cases, communication is necessary to inform all vehicles about the presence of the others, i.e., to increase cooperative awareness.

To overcome this problem, it has been proposed to use vehicles driving within communication range and Roadside Units (RSUs) as relay nodes and, thus, enable multi-hop beaconing [14]–[17]. Vehicles will not only broadcast their own state but also retransmit received beacons from other nodes. This approach could be shown to be effective and improve the cooperative awareness among all nearby nodes if the node density is high. This, however, requires both high traffic density and a high percentage of equipped vehicles (i.e., substantial market penetration of DSRC devices). As an example, we refer to our Adaptive Traffic Beacon (ATB) protocol as an approach that allows the seamless integration of infrastructure elements for multi-hop beaconing [14], [18].

However, in the early stage of IVC technology deployment, only a small percentage of all nodes will be equipped with on-board devices – thus reducing the likelihood of other equipped cars receiving a particular broadcast by another car. Furthermore, there will always be low traffic density areas in suburban regions – and, during off-peak hours and at night, traffic volumes can be expected to drop substantially even in the city center. Similarly, dense deployment of RSUs everywhere is unlikely due to the involved costs. Taken together, this means that low node densities will likely be the norm for new IVC systems.

In this paper, we therefore propose the utilization of *parked vehicles as relay nodes* [19] to route around obstacles as depicted in Figure 1. Parked vehicles will not transmit their own beacons informing other cars about their position and state, but only retransmit overheard beacons from moving vehicles. These relays (in contrast to RSUs) do not need to be bought, rented, or pre-deployed: whenever a DSRC equipped vehicle arrives at a destination, it can continue to serve as a relay.

Even though the use of parked cars has a number of advantages, one point warrants further investigation: Parked cars are not energy autonomous (their battery does not recharge while the engine is turned off). As, ideally, the use of parked vehicles as relay nodes should lead to no noticeable drawbacks for their owners, this means that there is an upper limit to how long parked cars can participate in IVC. We are able to show that our system can operate without problems for many days with negligible impact. This is particularly important as owners might not have a choice whether their vehicles participate in IVC: the U.S. Department of Transportation (US DOT) is evaluating DSRC deployment in a study that will be used to support a potential National Highway Traffic Safety Administration (NHTSA) 2013 decision to make DSRC mandatory [20].

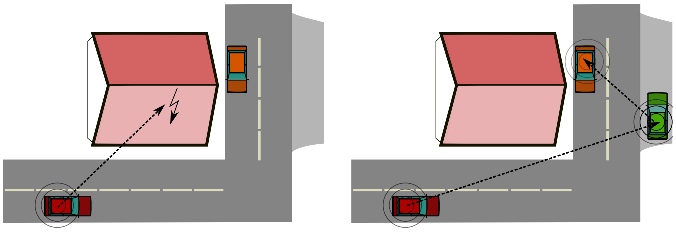

(a) houses block safety messages (b) 2-hop relaying via parked cars

Fig. 1. Utilization of parked cars as relay nodes can increase cooperative awareness in vehicular safety applications.

We show that in different scenarios cooperative awareness can be significantly improved. Thus, the safety of vehicles using such IVC applications can be positively impacted. Most recently, the concept of using parked cars as relays for Internet access has been described [21], [22]. However, to the best of our knowledge, we are the first to help overcome the aforementioned problems by making use of parked vehicles for cooperative awareness and safety applications.

Our key contributions can be summarized as follows:

- We study the use of parked vehicles as relay nodes for improving cooperative awareness and road traffic safety in urban and suburban environments, particularly when compared to ideally placed RSUs. This can be seen as a direct extension to recently presented beaconing approaches (e.g., the ATB protocol [14]).
- We examine whether and to what extent the usage of parked cars as additional nodes in Intelligent Transportation Systems (ITS) can increase the safety of vehicles. We do not aim to present a specific relay strategy scheme, although we acknowledge that intelligent algorithms would have to be applied.
- We aim to give an answer to the question whether parked cars should participate or stay silent when it comes to safety applications in urban and suburban areas.

The remainder of this paper is organized as follows. In Section 2, we discuss related work in this field of research. Subsequently, we present our approach to alleviating this problem by relaying beacons via parked vehicles in Section 3. We present and discuss results based on extensive simulative studies in Section 4. Finally, we conclude the paper with a short summary.

2 Related Work

In the following, we discuss relevant related work covering IVC and situation awareness.

For supporting undirected dissemination of information, e.g., for cooperative awareness applications, ETSI suggested CAM messages at fixed broadcasting frequencies in the range of 1 Hz to 20 Hz [23]. These include information such as speed, position, and heading.

There have been several publications on safety applications and cooperative awareness using periodic beacon messages [14], [24], [25]. All those systems concentrate on moving cars only.

Ros et al. proposed a beacon-based protocol to increase reliability of Vehicular Ad Hoc Networks (VANETs) while minimizing the number of beacon retransmissions [26]. In their approach, local position information is used by cars to determine whether they belong to a connected dominating set and subsequently reduce waiting periods before retransmissions. A similar approach, extended to a 2-hop neighborhood, was presented by Khan et al. [27]. They further exploit geographic location, speed, and direction information. Based on this information, nodes will produce retransmission strategies for periodic beaconing. 3-hop connectivity was investigated in the scope of the FleetNet project [28]. It has been shown that the available capacity on the wireless channel is sufficient to support safety protocols on these connections.

The main challenge for all beacon systems, however, is that they are very sensitive to environmental conditions such as vehicle density and network load. A first adaptive beaconing system was REACT [29]. Based only on neighbor detection, it can skip intervals for beacon transmission to support emergency applications. Recent approaches, also supported by ETSI, suggest to combine beaconing with geographical knowledge [30]. The resulting GeoCast provides means for more efficient channel use [31], [32].

The main challenge of adaptive beaconing is to dimension the system in such a way that the available capacity of the channel is carefully used in high density scenarios [14], [32]. This is to prevent what is commonly known as the broadcast storm problem [33], [34]. In selected cases, also the control of the transmission power helps increase spatial reuse of the wireless channel [35]. Recently, Decentralized Congestion Control (DCC) has been suggested in ETSI ITS-G5 building on earlier approaches to cope with congestion problems [36], [37].

The idea of placing road side infrastructure – backbone-connected RSUs or autonomous Stationary Support Units (SSUs) – in order to strengthen connectivity between moving nodes has also been discussed in literature. Lochert et al. studied the impact of connected SSUs to improve the performance of ITS applications in the roll-out phase [38]. They found that those static units can significantly improve connectivity between nodes. Furthermore, Ding et al. presented SADV, an approach that utilizes static nodes at road intersections in order to improve data dissemination in vehicular networks [39]. They use a store-and-forward algorithm to overcome problems in scenarios with low node densities.

Our own ATB protocol [14], [18] integrates beaconing between moving vehicles and available RSUs or SSUs by carefully observing the available channel capacity. Observing multiple metrics of both the contents and the communication channels, ATB adaptively controls the rate of broadcasts to (a) ensure communication with high reliability and (b) low-latency transmission of high priority messages, e.g., for safety applications. In a follow-up study we developed the Dynamic Beaconing (DynB) protocol [40] that even more aggressively makes use of available channel capacity.

Tang et al. investigated timings for collision avoidance systems [5] assuming DSRC transmission delays of 25 ms and 300 ms in normal and poorer conditions, respectively. They introduced the *time to avoid collision* metric, which represents the time from detecting a potential collision to the point of just avoiding a collision and concentrated on the events (when to warn a driver early and latest, reaction of driver, and different deceleration rates) within this time interval.

3G and 4G approaches are of course still investigated for this application scenario [41], [42], but out of scope for this work. In short, using cellular multicast techniques, it is possible to achieve low-latency communication within a single cell. Still unclear, however, is how to operate such networks if multiple operators are involved. In this case, a message cannot easily be reflected by the base station but needs to be transmitted through the entire backbone network of the two involved operators, thus, causing very high delays.

Our approach as presented in this paper complements all the mentioned concepts by introducing parked vehicles. Typically, those are already placed in advantageous positions – along urban streets. We show that safety applications greatly benefit from this approach, especially in the transitional phase, i.e., when IVC communication devices and SSUs are starting to be deployed in the market. Thus, employing parking cars as relay nodes should lend itself well to improve all listed approaches.

3 Utilizing Parked Cars

A detailed study of parking behavior in the area of Montreal, Canada offers interesting insights [43]: in 2003, out of 61 000 daily parking events, 69.2 % of all parked cars were parked on streets while only 27.1 % were parked on outside parking lots. A minority of 3.7 % was parked in interior parking facilities. On average the duration of one parking event was about 7 h. The study furthermore shows that parking vehicles were distributed throughout the whole city, which means there is a high possibility that a parking car is within transmission range of a moving car. Other studies found that, on average, a vehicle is parked for 23 h a day [44].

We therefore conclude that the use of parked cars as relays in vehicular networks can prove to be very helpful in supporting message exchange – at any given time, most cars are parking; of these, most are parking on streets. This concept is also supported by the recently presented work on using parked vehicles for distributed content download [21].

The general advantage of vehicles is that they are energy autonomous: as vehicles move, their battery is continuously recharged. However, parking nodes do not have this virtually unlimited supply of power as their battery does not recharge while the engine is turned off. We provide a discussion of the impact of the proposed relaying strategy on battery drain in Section 4.1.

This leaves the question of how likely it is that parked vehicles will be able to participate in a vehicular network. Technically, this can easily be solved: Just like their moving counterparts, parked vehicles are already equipped with DSRC devices. Modern cars already come pre-equipped with dedicated electronics to keep certain devices powered on when the vehicle is not driving – and cutting power to these devices when the battery charge drops below a certain point. Furthermore, high availability and market penetration of DSRC equipped cars can be predicted. Currently, the U.S. Department of Transportation (US DOT) is evaluating the scalability, security, and interoperability of DSRC devices and applications in its *Connected Vehicle Safety Pilot Program*, aiming to jumpstart commercialization in the automotive and consumer electronics. Further, the output of the study serves to support National Highway Traffic Safety Administration (NHTSA) 2013 rulemaking, such as whether to make DSRC mandatory [20].

Following this discussion, we argue that users will most probably be willing to join because of the following reasons: The availability of communication via parked cars can substantially improve cooperative awareness and, therefore, vehicular safety. Secondly, the success of social networks and of crowd sourcing activities demonstrates the general willingness to share information for mutual benefit. Given that the technical impact is very low, this might even become a motivation for mandated use, again, given the fact that road traffic safety can be substantially improved without the need to deploy an unreasonably (due to cost) high number of RSUs.

A benefit of parked cars is their parking position itself. Alongside the street and often near obstacles, they offer a promising possibility to relay beacon messages of driving cars in order to bypass obstacles. This idea is shown in Figure 1. Conceptually, parked vehicles represent a set of dynamic SSUs, participating in the vehicular network, e.g., to enhance the performance of safety applications. We see a major benefit in the ubiquitous availability of such parked cars in comparison to RSUs and SSUs.

Assuming that each moving car periodically emits beacon messages containing its position and speed, parking nodes will overhear these messages. A parked car will rebroadcast this beacon message so that other moving cars (which might be unaware of the original broadcast due to shadowing) will then pick up the beacon. Conceptually, we extend previous work on safety applications and examine the influence of parked cars on the success rate of such safety beacons. To cope with the broadcast storm problem and to keep channel load low, we limit the relaying of messages to 2-hop transmissions, i.e., a maximum of one relay node.

To obtain an upper bound for the safety benefit obtainable by utilizing parking vehicles as relay nodes, we made use of a very simple relaying system: Moving vehicles generate safety beacons with a time-to-live (ttl) value of 1. When another node receives one of these beacons, it decreases the ttl to 0 and retransmits it. Packets with a ttl of 0 are never rebroadcast. In a final system, a carefully designed relaying algorithm needs to be deployed in order to keep channel usage low but still ensure a benefit close to the upper bound which we present in this article. Possible solutions include the restriction of relaying to only special nodes, for example, nodes that are parked close to intersections [45]. Furthermore, a relaying node could be able to autonomously assess whether packet relaying helps improve cooperative awareness for nearby nodes by observing neighborship relations including movement information such as speed or direction [46]. Also, evaluating current channel conditions in order to determine whether a packet should be relayed seems to be a promising approach [18].

4 Evaluation

We performed extensive simulations to show the effectiveness of using parked cars to support safety applications in vehicular networks. In order to produce meaningful results, the underlying model has to be chosen very carefully. We investigated our scheme with the help of our simulation environment Veins [47]–[49], which is based on two dedicated simulation toolkits for road traffic and network traffic simulation, SUMO and OMNeT++, both well established in their respective domain.

Central metrics for information dissemination in VANETs are a node's number of available neighbors and, more importantly, the variability in connectivity, which influences metrics such as neighbor lifetime, stability, and network rehealing times. Accurate modeling of, e.g., the radios' transmission range and packet error rates are crucial to arrive at realistic neighbor counts, as this metric is heavily influenced by the choice of path loss model. Metrics like neighbor lifetime and network stability, however, can only be accurately simulated if the model also properly captures the effect of obstacles – which is done using the presented obstacle model for modeling realistic radio signal attenuation (cf. Section 4.3).

4.1 Impact of Relaying on Battery Drain

In this paper, we assume that parked cars are virtually energy autonomous. In order to motivate this assumption, we investigated the energy needed for providing relay services. A typical IEEE 802.11p On Board Unit (OBU) should not drain more than 1 W on average, which is a very generous upper limit. Considering a small car's battery providing 480 Wh to 840 Wh [50], we can run the system for 20 days, fully draining the battery. Assuming that we allow to use at most 10 % of the battery's capacity, we can still use the system for 2 days.

In conclusion, we can say that the use of such a relay system for a parking time of less than one day is without any critical impact on the usability of the vehicle. When considering bigger cars or hybrid cars, these numbers will be even better. For example, the battery of a Tesla Roadster has a capacity of 53 000 Wh providing energy for several years of constant radio transmission. Still, it is obligatory that the OBU of parked vehicles do not discharge the battery below a point where the car cannot be started again. There must always be enough power left for the ignition and other mandatory functions of the vehicle. Basically, there are two possibilities to overcome this problem. Either the on-board device knows about the battery level and can switch itself off accordingly, or the DSRC device is equipped with a dedicated battery that is also recharged when the car moves again. For the remainder of this paper, we assume that, without loss of generality, all cars always have enough energy left to operate the 802.11p OBU.

4.2 Simulation Setup

We investigate two different scenarios: a synthetic Manhattan Grid scenario and a realistic suburban scenario.

The Manhattan Grid scenario, true to its name, is based on regularly spaced vertical and horizontal two-way streets forming 270 m long and 80 m wide blocks; this block size is inspired by downtown Manhattan. We modeled blocks as homogeneous obstacles, allowed vehicles to park at arbitrary points on the curbside around them, and turned off all traffic lights.

The realistic suburban scenario is based on real geodata (i.e., road and building geometry, speed limits, right of way, one way streets, etc.) from OpenStreetMap for the city of Ingolstadt, Germany. We further adapted the data to reflect realistic intersection management (correct turning lanes, coherent traffic light phases).

Based on satellite data, we also added parking areas and distributed vehicles corresponding to the size of the parking area. In the simulation of these scenarios, cars were allowed to park anywhere in these areas, their locations following a random uniform distribution according to the findings presented in [43].

Serving as a baseline for comparison, we also deploy RSUs, which we can enable as relays as well. In order to provide optimal conditions for message dissemination via RSUs, they are deployed in a very optimistic fashion. RSUs are deployed on the busiest intersections first to maximize their impact and each RSU is positioned in the exact center of a junction to maximize its coverage. It should be noted that, for the examined 2-hop (i.e., 1 relay) forwarding scenario, RSUs do not need to make use of a backbone connection and are thus functionally equivalent to SSUs.

Driving vehicles used the *Krauss* microscopic driver model [51] implemented in SUMO and followed all traffic regulations. These vehicles were generated by randomly selecting Origin/Destination pairs describing their departure location and destination, then iteratively applying dynamic user assignment [52] until the algorithm reported a stable, optimal distribution of flows.

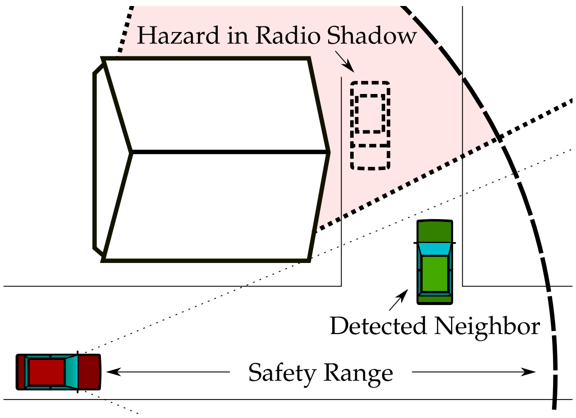


Fig. 2. Illustration of the primary evaluation metric, the ratio of detectable cars within a predefined safety range. The lower left car can detect one of two cars in its safety range; the other car is hidden in the building's radio shadow.

TABLE 1
Parameters and terminology

Density of moving (equipped) cars	ρ cars/km^2
Density of parked (equipped) cars	σ parkers/km^2
Density of Roadside Units (RSUs)	ω RSUs/km^2
Beacon interval	1000 ms
Safety range	400 m
ROI size	1.5 km^2
Simulation Framework	Veins (OMNeT++, SUMO)
Path-loss model	obstacle pathloss [7]
Medium access	idealized

In our evaluation, we focus on a 1.5 km^2 Region of Interest (ROI), which contains a typical mixture of high- and low-capacity roads, traffic lights, and unregulated intersections, as well as high and low node density areas. To avoid border effects, we simulated traffic in in the whole city of Ingolstadt, but only investigate nodes driving within the ROI.

In both scenarios all moving vehicles (but no parking vehicles) emit beacon messages (representing CAMs messages) once every second. The beacons could then be relayed in a 2-hop fashion by nodes in the immediate neighborhood. We configured these relaying nodes to re-transmit beacons only after a short random processing time of 1 ms to 10 ms. Depending on the simulated configuration we enabled a different subset of relays: either driving cars only, parked cars only, RSUs only, or a combination of moving vehicles and one type of stationary nodes.

Measuring the level of safety that the ITS application affords at a global scale is, in general, a difficult task. One would have to identify certain classes of constellations between vehicles, obstacles, and parked cars in order to give an absolute insight whether safety has improved or not. The classification of these cases, however, is an open challenge and a 100 % coverage of all cases cannot be guaranteed [53].

Therefore, we chose as the primary metric in our simulation the ratio between the number of potential neighbors in a theoretical maximum safety range (cf. Figure 2) and the amount of these nodes that could actually be reached with a beacon message (using our obstacle model, cf. Section 4.3).

We thus obtain a ratio describing the *reachability* of nodes in the network. The safety range (which corresponds to a maximum unobstructed transmission range of a node) was configured to be 400 m, as we believe that nodes further away do not play an important role for safety applications in urban environments. Please note that we only use this safety range to measure the benefit gained from beacon-relaying parked vehicles and RSUs; it is not used in the calculation of radio propagation.

In order to be able to obtain baseline measurements, we employ a modified IEEE 802.11 medium access scheme that is idealized (collision free). This allows us to abstract away from the effects that real-world protocols would necessarily need to introduce in order to coordinate fair and scalable medium use. We can thus give an upper bound on the number of possible data transmissions that is independent of the used protocol.

For easy reference, Table 1 gives an overview of parameters and terminology used in the following discussion.

4.3 Obstacle Model

The impact of obstacles in suburban environments is also very evident when considering two vehicles that are driving on parallel roads separated by irregularly spaced buildings: here, channel conditions for transmissions between both nodes might quickly alternate between a near-perfect, lossless channel and strong (but predictable) shadowing. It has thus become a well-established fact that realistic path loss models, which also capture effects like shadowing, are crucial to the quality of a wide range of VANET simulations [9], [54]–[58]. In previous work, we developed a computationally feasible but still very accurate shadow fading model for IEEE 802.11p [7].

Simulating path loss in (sub)urban environments to capture predictable shadowing effects seems to require more complex models than *attenuation per wall* or *attenuation per meter of penetration* approaches. In theory, precise modeling of radio propagation in such environments is possible by using a ray-tracing approach using detailed geodata, but (as shown in related work) the computational effort to employ this approach for large scale IVC simulations is prohibitively high. In a similar vein, modeling effects such as reflection and diffraction requires geodata with a level of detail that is unlikely to be available at the required scale.

Thus, our motivation was to develop a model that only relies on building outlines, which are commonly available in freely available geodata, and thus needs to abstract from reflection and diffraction effects. Furthermore, in order to keep the model computationally inexpensive, it considers the line of sight between sender and receiver only; it disregards any objects blocking, e.g., parts of the first Fresnel zone.

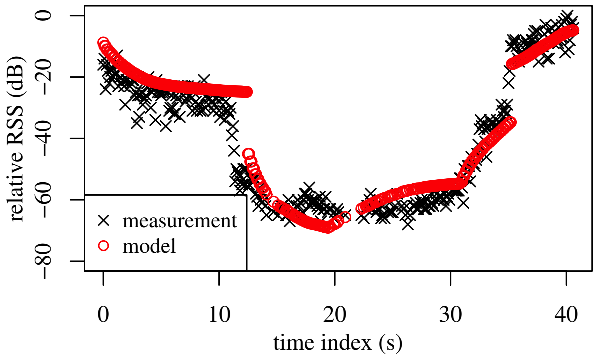


Fig. 3. Comparison of RSS measurement campaign to values predicted by our model (shown for a countryside warehouse).

This way, simulations that make use of the model scale very well, the calculation of intersection between all lines of sight and all buildings being its most expensive step. Finding these intersections can further be supported using caching and binary space partitioning approaches [59] to solve this step in $\mathcal{O}(n^2 \log n)$ time. Finally, depending on the employed simulation framework, this process can also be treated as a *red and blue line segments* intersection problem, for which algorithms that run in $\mathcal{O}(n \log n)$ time have been proposed [60].

Analogous to those in related work [59], [61], [62], we envision our model to be a generic extension of well-established fading models. In general, these can be expressed in the form of Equation 1, where P are the transmit (or receive) powers of the radios, G are the antenna gains, and L are terms capturing loss effects during transmission.

$$P_r[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \sum L_x[dB] \quad (1)$$

Common models of large-scale path loss, of deterministic small-scale fading, or of probabilistic attenuation effects can then be written as components L of Equation 1 and, thus, chained to calculate the compound attenuation. Equations 2 and 3 illustrate this for the examples of two-ray ground path loss and log-normal shadow fading, respectively.

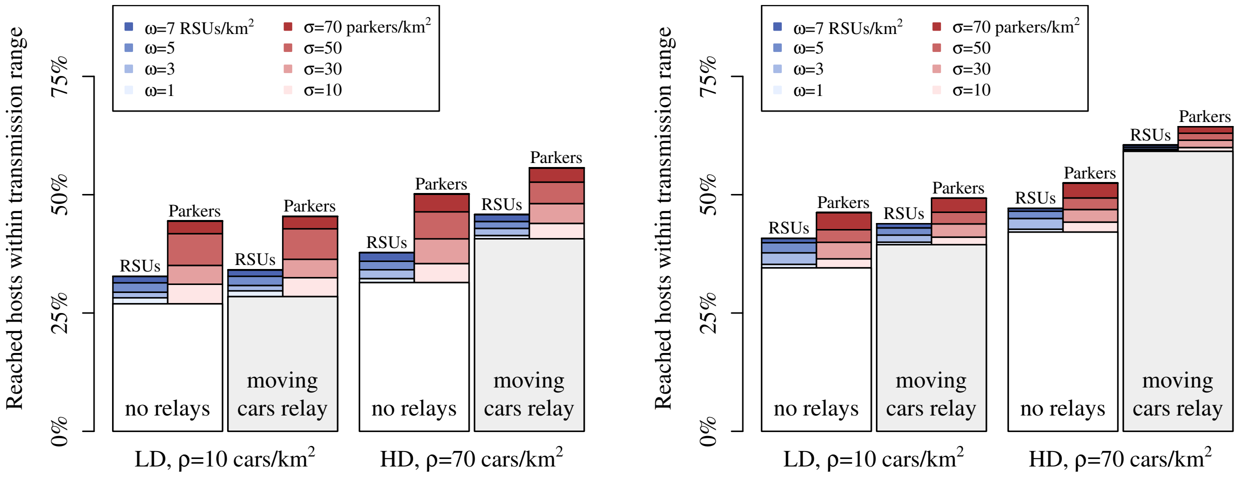
$$L_{tworay}[dB] = 10 \lg \left(\frac{d^4 L}{h_t^2 h_r^2} \right) \quad (2)$$

$$L_{lognorm}[dB] = 10 \lg (X_\sigma) \quad (3)$$

We extended the general model shown in Equation 1 by contributing another term L_{obs} to be used for each obstacle in the line of sight between sender and receiver. In [7] we show that its structure can be derived as

$$L_{obs}[dB] = \beta n + \gamma d_m \quad (4)$$

L_{obs} is intended to capture shadow fading due to a building, based on the number of times n the border of



(a) Manhattan Grid

(b) Suburban Scenario

Fig. 4. Comparison of beacon relay approaches in suburban and Manhattan Grid scenarios at both low node density (LD, $\rho = 10\,\text{cars/km}^2$) and high node density (HD, $\rho = 70\,\text{cars/km}^2$). For each scenario, results of four different relay configurations are plotted: using only RSUs as relays, only parked vehicles as relays, as well as using RSUs or parked vehicles in addition to moving vehicles.

this obstacle is intersected by the line of sight and the total length d_m of the obstacle's intersection. The first of the two calibration factors, β, is given in dB per wall and represents the attenuation a transmission experiences due to the (e.g., brick) exterior wall of a building. The second calibration factor, γ, is given in dB per meter and serves as a rough approximation of the internal structure of a building.

This parameterization allows the model to be intuitively adjusted to represent shadowing effects of different kinds of buildings in (sub)urban settings.

We evaluated how well the shadowing model presented in Equation 4 can capture the predictable changes in path loss caused by buildings [7], combining it with the generic and free space path loss models shown in Equations 1 and 5, respectively, to arrive at Equation 6.

$$L_{freespace}[dB] = 10\lg\left(\frac{16\pi^2}{\lambda^2}d^\alpha\right) \tag{5}$$

$$P_r[dBm] = P_t[dBm] + 10\lg\left(\frac{G_t G_r \lambda^2}{16\pi^2 d^\alpha}\right) - \beta n - \gamma d_m \tag{6}$$

In order to determine to what extent changes in measured RSS could be explained by this model, we examined whether parameters β and γ could be fitted so that analytical results would match up with measured ones. Parameter fitting was performed by iteratively minimizing the sum of squared residuals using the standard Gauss-Newton algorithm [63] until the algorithm converged, based on a tolerance threshold of 1×10^{-5}.

Figure 3 shows selected results of this process for a representative set of measurements in the countryside. Here, we circled a free-standing warehouse, obtaining parameters of $\beta = 9.2\,\text{dB}$ per wall and $\gamma = 0.32\,\text{dB/m}$. We observe that β and γ are within the expected range and, in general, computed values for the attenuation match the values we measured quite well. The plotted values also demonstrate that the model only considers the line of sight, rather than the first Fresnel zone, between sender and receiver: the smooth decrease of measured RSS values that can be observed as the line of sight is not yet crossing the first corner (but the building's intersection with the Fresnel ellipsoids is starting to increase) at 10 s is replaced by a sudden drop in RSS values in the analytical model.

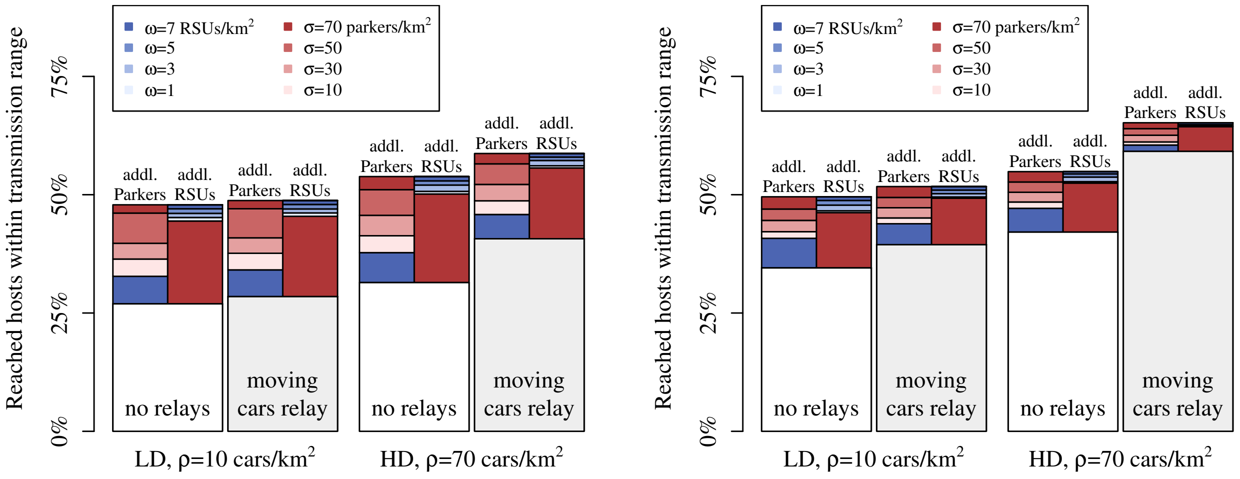
Similar observations have been made for other measurement series, of light construction, brick, and mixed material buildings, in suburban and urban environments [7]: in each case the model was able to predict the qualitative effects of shadowing (and, after model fitting, matched measurements within the abovementioned margins).

4.4 Impact of Obstacle Shadowing and Relaying

In a first step, we examined the influence of obstacle shadowing on the number of reachable hosts within a theoretical safety range and how relaying of safety messages – by routing around obstacles – can improve the situation. The metric we used was the ratio of actual reached moving vehicles to the amount of theoretical reachable moving vehicles within the safety range.

Figure 4 illustrates that obstacles reduce the number of reachable hosts drastically: without relaying the percentage of reached hosts was around 25 % to 30 % in both the low node density (LD, $\rho = 10\,\text{cars/km}^2$) and high node density (HD, $\rho = 70\,\text{cars/km}^2$) scenario. This is in line with other findings demonstrating a minimum rate of equipped vehicles for successful ITS operation [24].

We then enabled relaying exclusively on either RSUs or parking vehicles. For the core of this work, the use of parking cars, we were able to reveal that in the Manhattan



(a) Manhattan Grid (both RSUs and Parkers)

(b) Suburban Scenario (both RSUs and Parkers)

Fig. 5. As Figure 4, but when complementing maximum RSUs deployment with a varying number of parking vehicles, or deploying a varying number of additional RSUs to support parked vehicles.

Grid scenario (Figure 4a) parked car relaying had a pronounced effect: for both the LD and HD scenario the amount of reachable vehicles was considerably increased and clearly outperformed regular VANET broadcasting. The reason for this is that in this synthetic Manhattan scenario every parked car is a good relay node candidate, as it parks on the curbside next to a building. There were no ineffective parked vehicles like in the suburban scenario (Figure 4b), where parking spaces are not necessarily located next to a building but in areas not suitable for relaying around obstacles; here, the amount of newly reached vehicles is accordingly lower.

As a core outcome of this paper, this evaluation allows comparing the performance of parked cars to that of optimally placed RSUs. We observe that, in the suburban and the Manhattan Grid scenarios, as little as $\sigma = 30\,\mathrm{parkers/km^2}$ and $\sigma = 15\,\mathrm{parkers/km^2}$, respectively, yield the same level of cooperative awareness as $\omega = 7\,\mathrm{RSUs/km^2}$ – yet, with zero deployment cost.

By enabling relaying on moving nodes only, the ratio merely marginally improved for the low density scenarios, while it helped reaching a considerably higher percentage of nodes when the traffic density was high. When additionally enabling relay functionality on one type of the stationary nodes, we can even further increase the level of cooperative awareness. The gain when adding stationary relay nodes is again higher in a low density scenario than for the high density scenario. We also observe that the set of nodes additionally reached with the aid of stationary nodes is not a subset of the nodes reached with moving vehicles, as the number of reached hosts still increased.

In a second step, we investigate the benefits of relaying when both parked cars and RSUs are present. Figure 5 illustrates our findings for both the Manhattan Grid and the suburban scenario. The figure can be read similar to Figure 4: the left of the stacked bars always shows the benefit of parking vehicles (shaded red boxes) on top of a maximum number of deployed RSUs ($\omega = 7\,\mathrm{RSUs/km^2}$, blue box) and with or without the help of driving vehicles (white or gray box, respectively). Correspondingly, the right bars show how different numbers of RSUs (shaded blue boxes) improve the situation when there is already a high number of parking vehicles ($\sigma = 70\,\mathrm{parkers/km^2}$, red box) present.

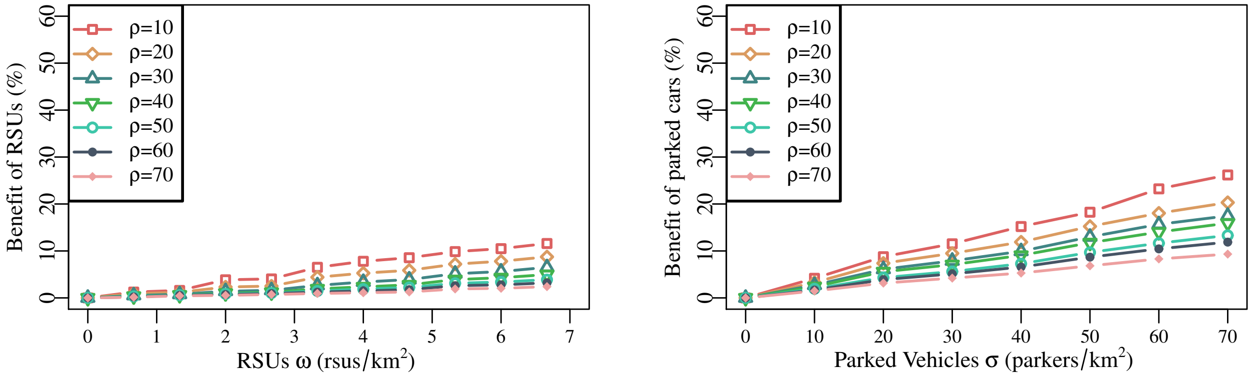
We note that the addition of parking vehicles always leads to a substantial additional benefit, while even very dense deployments of RSUs (which will likely be prohibitively expensive) only marginally improve the situation when parking cars are already utilized. This is very visible in the Manhattan Grid scenario (Figure 5a), independent of the density of moving cars, while, in contrast, there is a clear difference between low and high density in the suburban scenario (Figure 5b). We thus conclude that, especially at low densities (i.e., nighttime), the use of parked vehicles has huge potential to help RSUs bridge communication gaps, improving safety.

4.5 Relaying Benefit of Parked Cars and RSUs

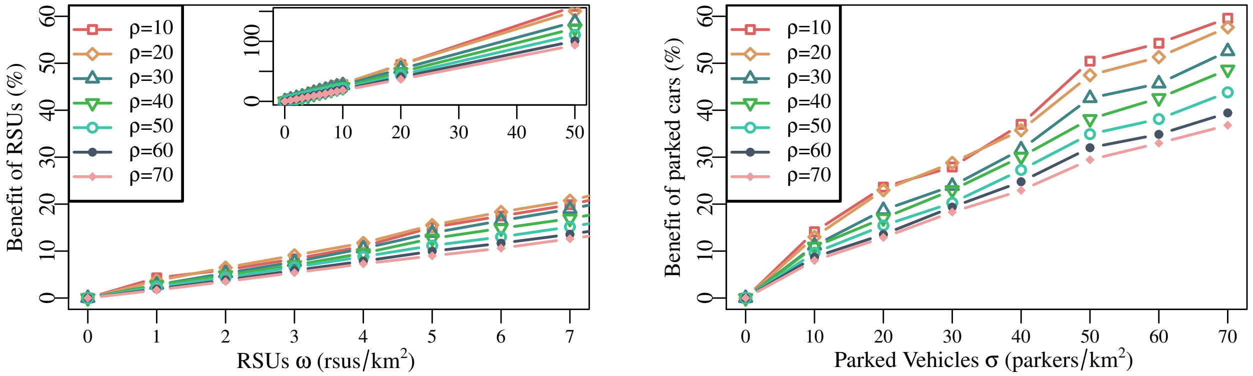
In order to get more detailed insights in which situations RSU and parked car relaying help increase cooperative awareness, we investigated the beneficial effects in extensive simulative studies parameterizing both node density and the amount of stationary nodes.

For this purpose, we refer to the used metric as the benefit, i.e., the amount of additionally reached cars relative to the number of cars reached with moving vehicle relaying only.

In all setups presented in Figure 6, we observe that the benefit of stationary support nodes, that is parking vehicles or RSUs, is higher when the node density ρ is lower. With more driving vehicles in the network, the



(a) RSUs, Suburban scenario (b) Parked Cars, Suburban scenario



(c) RSUs, Manhattan Grid (d) Parked Cars, Manhattan Grid

Fig. 6. Increase in message delivery success when additionally using RSUs or parked cars as relay nodes.

probability of a vehicle previously being unreachable due to a blocked radio signal but reachable through an intermediate driving vehicle increases – reducing the benefit of stationary nodes.

Comparing performance of parking car and RSU relaying in a suburban context (Figures 6a and 6b), we observe that even when placing RSUs at the most frequented junctions with a density of $\omega \approx 6.7\,\mathrm{RSUs/km^2}$ the benefit does not exceed 10 %. By utilizing the readily available parked cars in the area we observed peak values of up to some 25 %.

In this scenario, the amount of deployed RSUs is evidently lower than the number of parked vehicles, however, we argue that it is unlikely that in a suburb the density of deployed RSUs exceeds the number of simulated nodes, though for the parked vehicles we consider even a density of $\sigma = 70\,\mathrm{parkers/km^2}$ as realistic.

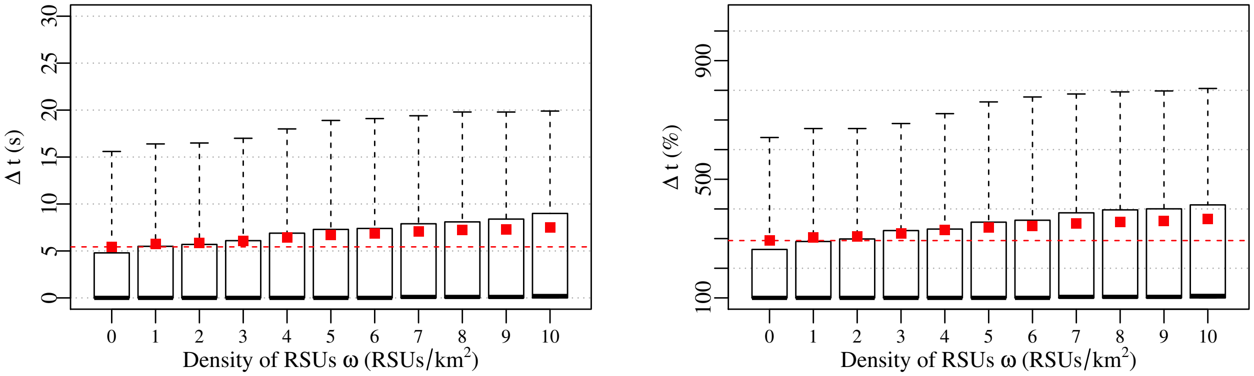
For the Manhattan Grid scenario (Figures 6c and 6d), obstacle shadowing is much more pronounced, thus, the benefit obtained from relaying via stationary nodes is higher than in a suburban area. We observe that compared to the suburban setup the benefit per deployed stationary node has changed in favor of the parked vehicles: for example, it only takes about $\sigma = 20\,\mathrm{parkers/km^2}$ to reach the same amount of vehicles as with $\omega = 7\,\mathrm{RSUs/km^2}$. Equipping near to every junction with a Roadside Unit (Figure 6c, top right) would lead to an almost perfect coverage, improving cooperative awareness by up to 150 %, but at unrealistically high costs.

We conclude that in areas with heavy signal obstruction – such as Manhattan Grid – the aid of parked cars can considerably boost cooperative awareness and therefore reduce the number of RSUs needed. In a more open area, RSUs can only marginally increase the amount of reachable hosts, unless deployed in an excessive number. This issue can be overcome by the aid of parked cars, which should be available in high numbers in suburban residential neighborhoods.

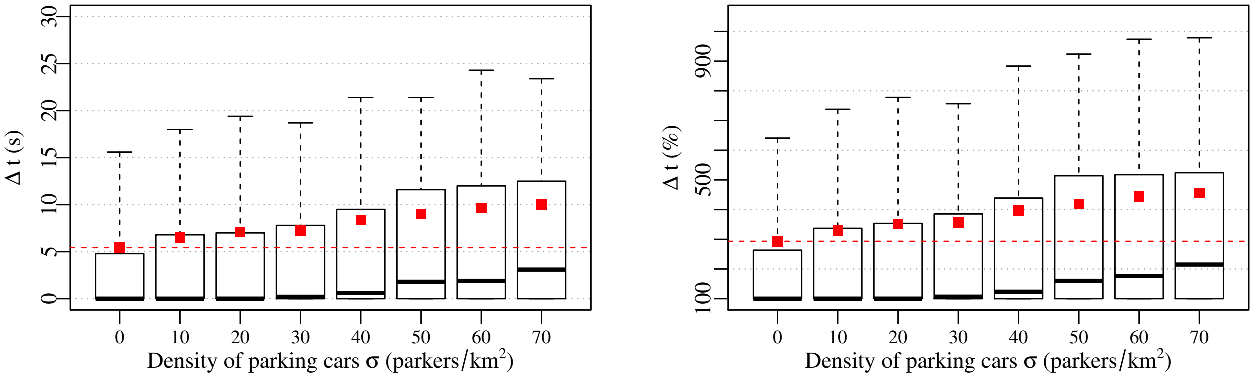
4.6 Earlier Notification as a Safety Metric

When investigating safety applications in vehicular networks, not only the amount of cars reached by a broadcast message is relevant, but also how early vehicles are aware of the existence of a nearby car. The earlier an in-car safety system knows of the presence of another vehicle, the earlier it can notify the driver or prepare active and passive safety systems.

For each pair of vehicles we therefore tracked when they first became aware of one another, taking their time of receiving the first safety message (t_{known}). We also tracked how much later these two vehicles actually met at an intersection, taking their time of closest distance (t_{met}). We term this time difference ($t_{\mathrm{r}} = t_{\mathrm{met}} - t_{\mathrm{known}}$) the drivers' afforded reaction time.



(a) RSUs, absolute time difference (b) RSUs, relative time difference



(c) Parking Cars, absolute time difference (d) Parking Cars, relative time difference

Fig. 7. Additional afforded reaction time Δt_r in critical situations ($t_\mathrm{r} \leq 3\,\mathrm{s}$ without relaying): time difference achieved when enabling relaying via moving vehicles only ($\omega = \sigma = 0$) as well as when supported by either RSUs ($\omega > 0$) or parked cars ($\sigma > 0$). Plotted are results for the low density Manhattan Grid scenario ($\rho = 30$).

Without the ability to relay messages, buildings would frequently keep vehicles from exchanging safety messages, leading to the afforded reaction time frequently falling below a critical threshold [10] of 3 s.

We isolate only these critical situations (those where $t_\mathrm{r} \leq 3\,\mathrm{s}$ without relaying) and investigate to what extent each could be mitigated by allowing relaying via moving vehicles, supported by either parked cars or RSUs. We quantify the achieved safety benefit as the difference Δt_r in afforded reaction time when enabling relaying.

The results are displayed in Figure 7 in the form of a box plot. The boxes reach from the 25 % to the 75 % quantile while the whiskers extend to the 90 % quantile. The bold line marks the median. As the distribution of the recorded data was heavy-tailed, we also plot the mean of recorded values (small red squares).

We investigate the Manhattan Grid with a fixed low node density of $\rho = 30\,\mathrm{cars/km^2}$. We observe that for 50 % of all cars there is no improvement when allowing only moving nodes to relay messages ($\omega = \sigma = 0$).

Adding RSUs to support relaying (cf. Figures 7a and 7b) can add valuable extra seconds to the afforded reaction time, albeit only for a small portion of drivers. This stems from the fact that an RSU can only help improve safety at the particular junction at which it is placed.

Thus, even very high deployment densities of $10\,\mathrm{RSUs/km^2}$ do not suffice to noticeably increase the median time benefit above 0 s.

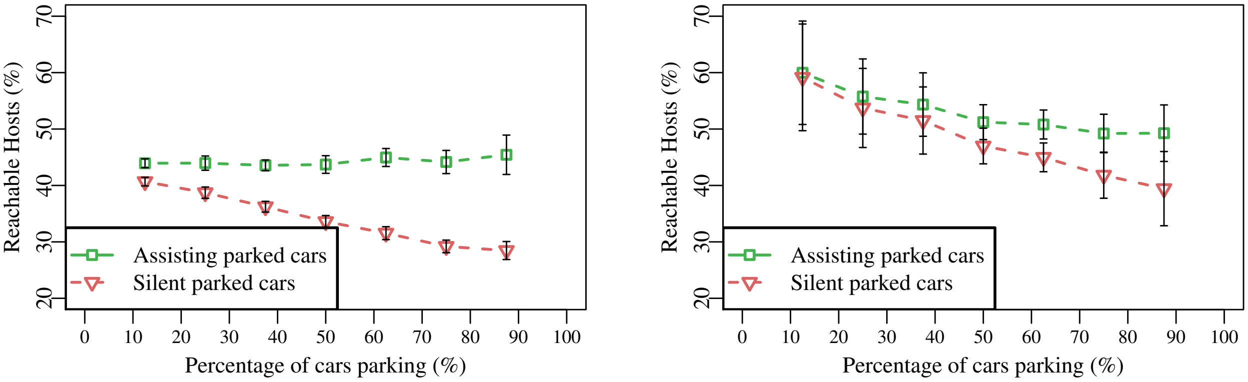
This is in contrast to results obtained by enabling relaying via parked vehicles, of which a much higher number is available (cf. Figures 7c and 7d). Even a small portion of parked vehicles ($\sigma \geq 40\,\mathrm{parkers/km^2}$) results in a clear temporal improvement, giving at least 50 % of drivers valuable extra seconds to react.

Finally, if the full number of $\sigma = 70\,\mathrm{parkers/km^2}$ are available, afforded additional reaction times rose to levels that might now allow at least half of all critical situations to be defused.

4.7 Relaying Benefit in the Day/Night Cycle

In a last step, we examine the effect of moving vehicles becoming parking ones. This scenario can be understood as the typical day-night-scenario where the amount of moving vehicles constantly decreases in the evening and reaches a minimum sometime in the night. Those vehicles, however, may still be parking along the street and can therefore be used as relay nodes in a vehicular network.

In our setup, we considered the amount of total vehicles $\rho + \sigma$ as invariant, but varied the ratio $\frac{\rho}{\sigma}$.



(a) Manhattan Grid

(b) Realistic Scenario

Fig. 8. Percentage of hosts reached within the safety range plotted for a typical day-night-scenario. While the density of active nodes in the scenario is invariant ($\rho + \sigma = 80$), the ratio of moving to parking vehicles ($\frac{\rho}{\sigma}$) decreases. Error bars visualize the standard deviation of the dataset.

Our findings are presented in Figure 8. For the suburban scenario, we observe that we cannot quite keep the level of hosts reached within the safety range when the number of moving nodes decreases. However, without parking cars as relay nodes, this curve drops considerably faster. In the synthetic Manhattan Grid scenario, the effect of aiding parked cars is again clearer. Although the density of moving nodes ρ became lower and lower, the lack of relaying moving nodes could be completely compensated by parked cars. The percentage of reachable hosts within the safety range only varied marginally (green line) when moving vehicles further participated in the network as parking ones. In contrast to that, the level of awareness considerably dropped when this was not the case (dashed red line).

However, cooperative awareness is particularly important at night, when lighting conditions might be bad yet drivers more inclined to drive faster on the now almost empty streets. With the help of parked cars, vehicles can experience the same level of cooperative awareness at night, as if there were still many more moving vehicles on the street.

Independent from day and night, we furthermore conclude that with parked cars we can achieve the same level of cooperative awareness in sparsely populated areas as we would have in those with many moving vehicles.

5 Conclusion

The benefit of safety applications in vehicular networks is critically reliant on being able to communicate in a timely manner, even (and particularly) if direct connectivity between vehicles is precluded by obstacles such as buildings. This requires the use of other nodes for relaying safety messages periodically emitted by moving vehicles.

Two types of nodes are commonly considered to fulfill this role. First, moving vehicles; yet, this requires a sufficiently high number of equipped vehicles, which might not be available at night, in the evening, or in suburban areas. Secondly, static RSUs; yet, this incurs deployment costs that might be prohibitively high, particularly in suburban areas.

We propose the use of parked cars as relay nodes for safety messages. We showed that especially, but not exclusively, in areas of low node density, where parked cars are readily available, the amount of nodes that can be reached with safety messages can be substantially increased. We furthermore showed that vehicles can encounter each other considerably earlier when parked cars act as relay nodes. This extra time for drivers to respond to a certain traffic situation can translate to a reduction of accidents.

In suburban scenarios an unreasonably (due to cost) high number of RSUs would have to be deployed in order to achieve the same cooperative awareness that is possible with the aid of parked cars. Furthermore, in city centers (corresponding to a Manhattan Grid scenario) the number of RSUs can be drastically reduced while maintaining the same level of cooperative awareness.

Lastly, we found that, with the aid of parking cars, the loss of cooperative awareness due to the decreasing number of moving vehicles at night can be completely countered in a Manhattan Grid scenario, and substantially reduced in a realistic suburban environment.

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