

# Exploiting Beacons for Scalable Broadcast Data Dissemination in VANETs

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## ABSTRACT

Vehicular Ad-hoc Networks (VANETs) enable the timely broadcast dissemination of event-driven messages to interested vehicles. However, when dealing with broadcast communication, suppression techniques must be designed to prevent the so-called broadcast storm problem. Numerous suppression schemes aim to reduce broadcast redundancy by assigning vehicles to different delay values, i.e., time slots, that are inversely proportional to their distance to the sender. In this way, only the farthest vehicles would rebroadcast, thereby allowing for quick data dissemination. Despite many efforts, current delay-based schemes still suffer from high levels of contention and collision when the number of vehicles rebroadcasting nearly simultaneously is high in dense networks. Even choosing appropriate values for the total number of time slots does not prevent situations where simply no vehicle is assigned to the earliest time slot, what may result in high end-to-end delay. In this paper, we tackle such *scalability* issues with a scheme that controls with precision the density of vehicles within each time slot. To reach this goal, we exploit the presence of beacons, periodic messages meant to provide cooperative awareness in safety applications. Simulations results show that our protocol outperforms existing delay-based schemes and is able to disseminate data messages in a scalable, timely, and robust manner.

## Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Distributed networks, wireless communication

## General Terms

Algorithms, Performance, Reliability

## Keywords

Vehicular Ad-hoc Networks (VANETs), Vehicular Sensor Networks (VSNs), Data Dissemination, Broadcast Storm

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VANET'12, June 25, 2012, Low Wood Bay, Lake District, UK.  
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## 1. INTRODUCTION

Vehicular Ad-hoc Networks (VANETs) have gained considerable attention in the past few years due to their promising applicability with regard to safety, transport efficiency, and entertainment [6]. Vehicles rely on diverse built-in sensors to continuously gather, process, and disseminate relevant sensor data. For many applications, the data acquired by sensors is of public interest and must be broadcasted (disseminated) to all vehicles nearby, e.g., data about accidents.

However, several challenges arise when disseminating data based on broadcast communication. Broadcasting with the typical carrier sense multiple access with collision avoidance (CSMA/CA) mechanism present in the 802.11p standard is particularly unreliable due to the lack of acknowledgments. Also, vehicular networks are very dynamic with large deviations in density depending on the current road traffic. Therefore, protocols designed for VANETs must cope with diverse traffic conditions. In dense networks, a pure flooding scheme results in excessive redundancy, contention, and collision rates [11], which is referred to as the *broadcast storm problem*. Such problem is tackled with *broadcast suppression techniques*. Conversely, in sparse networks vehicles may face network disconnections when the transmission range employed cannot reach other vehicles farther in the direction of interest. In such scenarios, protocols should also incorporate a *store-carry-forward* mechanism to take advantage of the mobility of vehicles to store and relay messages until a new opportunity for dissemination emerges.

To cope with dense networks, numerous suppression techniques aim to assign vehicles to different delay values that are inversely proportional to their distance to the sender. In this way, only the farthest vehicles would rebroadcast, thereby allowing for quick data dissemination [29]. Vehicles assigned to delay values sufficiently higher to hear a rebroadcast echo can suppress their transmissions. This separation in time is accomplished by means of time slots, where each time slot is equivalent to a message's transmission time. However, in dense networks the number of vehicles rebroadcasting nearly simultaneously in a single time slot can increase considerably, thereby still leading to undesirable levels of contention and collision [12]. Since time slots match regions within the transmission range of the sender, another problem occurs when there is simply no vehicle assigned to the earliest time slot, what increases the end-to-end delay.

In this paper, we propose the **Distributed Optimized Time (DOT)** slot as a suppression scheme for dense networks. We focus on solving *scalability* issues of current approaches by controlling with high precision the density of vehicles within

each time slot. To accomplish this goal, we exploit the presence of beacons, which are messages periodically sent by each vehicle containing information such as the vehicle’s position and speed. While the use of periodic beacons or *hello* messages has been sometimes avoided due to an increase in the network load [29], beacons have been an important topic of research and are expected to be massively present to increase cooperative awareness in safety applications [19].

The remainder of this paper is organized as follows. Section 2 reviews and outlines problems with current suppression techniques. Next, Section 3 describes DOT in detail. Section 4 describes the performance evaluation of the protocol carried out by means of simulations. Finally, Section 5 concludes this paper and outlines our future directions.

## 2. RELATED WORK

Various broadcast suppression techniques have been proposed to prevent the so-called *Broadcast Storm Problem*. The ultimate goal is to select only the set with the minimum number of vehicles to rebroadcast and disseminate a message towards the region of interest.

In the context of Mobile Ad-Hoc Networks (MANETs), several solutions to address this problem were proposed and outlined in [11, 28]. In [28], authors present a comprehensive comparison study of various broadcasting techniques in MANETs organized into four categories: (i) *simple flooding methods*, without any form of suppression; (ii) *probability based methods*, that rely on network topology information to assign a probability for each rebroadcast; (iii) *area based methods*, which use distance information to decide which nodes should rebroadcast; and (iv) *neighbor knowledge methods*, which maintain state on the neighborhood via periodic hello messages to decide on the next forwarding node. However, these solutions are mostly concerned with providing means for route discovery with minimum extra network load and, therefore, do not take into account the highly dynamic environment present on roads, neither exploit specific characteristics of vehicular networks such as the predictable mobility pattern of vehicles’ movements.

In VANETs, it is generally assumed that each broadcast data message relates to a certain event of a specific geographical region and, thus, it is targeted mostly to vehicles traveling through that region. With this goal, protocols that rely on positioning information falling into categories (iii) and (iv) are most suitable. In category (iii), nodes in the Location-Based scheme [11] rebroadcast whenever the additional coverage is higher than a pre-defined threshold. In category (iv), most protocols require nodes to share 1-hop or 2-hop neighborhood information with other nodes [10, 14, 13]. This is particularly not suitable in vehicular environments, since such information can quickly become outdated due to the high speed of vehicles. In addition, adding neighborhood information to periodic messages results in high network overhead. As pointed out in [21], decreasing message overhead is crucial for leaving sufficient bandwidth for even-critical messages. In view of these drawbacks, several protocols have been proposed specifically for VANET applications. Such protocols present lightweight solutions in terms of overhead and elaborate on previous solutions in category (iii) such as in [11] in order to control, based on distance, the thresholds determining when vehicles should rebroadcast. In the following, we select and describe a few

of these efforts. For a complete survey of solutions, we refer the reader to [12].

The common approach to reduce broadcast redundancy and end-to-end delay in VANETs is to give highest priority to the most distant vehicles towards the message direction. In [29], three ways of assigning this priority are presented: Weighted p-Persistence, Slotted 1-Persistence and Slotted p-Persistence. In the first scheme, the farthest vehicles rebroadcast with highest *probability*. In the second approach, vehicles are assigned to different time slots depending on their distance to the sender, where vehicles with highest priority are given the shortest *delay* before rebroadcasting. Finally, the third approach mixes probability and delay by giving vehicles with highest priority the shortest delay and highest probability to rebroadcast. In delay-based schemes, vehicles assigned to later time slots have time to cancel their transmissions upon the receipt of an echo. This would be an indication that the information has already been disseminated and redundant rebroadcasts can be *suppressed*. Notably, to achieve the lowest possible end-to-end delay, deterministic approaches such as Slotted 1-Persistence should be preferred over probabilistic methods such as Weighted p-Persistence and Slotted p-Persistence. The reason lies in always guaranteeing that the farthest vehicle is chosen, which is not the case with probabilistic-based methods.

Delay-based schemes have been used in several other works with the goal of reducing rebroadcast redundancy, e.g., [4, 8, 2]. In [4], the Contention-Based Forwarding scheme (CBF) is presented. Authors focus on a distributed delay-based scheme for mobile ad hoc networks that requires no beaconing information. In [8], the Urban Multi-hop Broadcast (UMB) protocol is designed to cope with broadcast storm, hidden node, and reliability problems of multi-hop broadcast in urban areas. UMB has a special operation mode for scenarios with intersections. Nevertheless, it relies on the same time slotted principle for directional data dissemination. Finally, authors in [2] focus instead on a content-based data dissemination scheme. Information such as data relevance is used to define whether or not a vehicle should rebroadcast a data message. Although with a different primary goal, the proposed protocol is complemented with a delay-based scheme based on the vehicles’ distance from the sender to limit the bandwidth used.

Although efficient in tackling the broadcast storm problem, delay-based schemes still present scalability issues when not employed with optimal parameters. One clear limitation in most schemes proposed is the inability to dynamically choose the optimal value for the number and boundaries of the time slots used. As shown in Figure 1(a), time slots are usually matched to geographical regions within the transmission range of the sender. However, this can lead to an uneven distribution of vehicles in each time slot. Since transmissions in a single time slot occur nearly simultaneously (see [1]) and cannot be canceled, the level of rebroadcast redundancy and collision is unnecessarily increased. To cope with collisions, authors in [24] introduced the concept of *micro* slots to separate in time transmissions assigned to a single time slot. Another consequence of relying on fixed time slot parameters is that there might simply be no vehicle in one of the time slots, thereby increasing end-to-end delay of a message. In this line, the work in [22] introduces a means to control the number of time slots according to the network

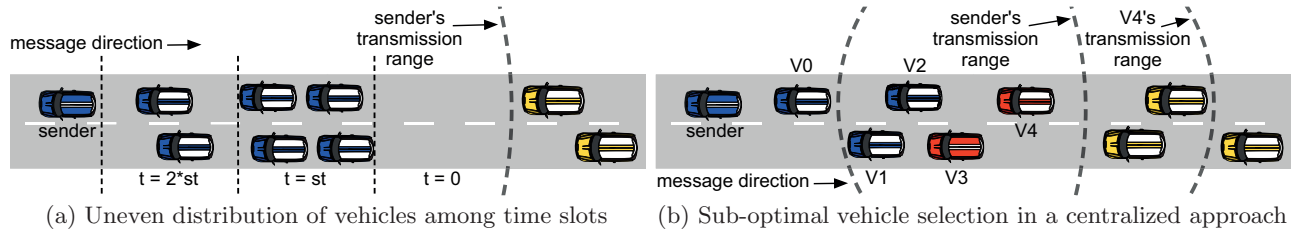


Figure 1: Overview of problems with current suppression approaches

density. However, authors do not cope with the problem of nearly simultaneous transmissions in a single time slot.

One way to tackle the problem of uneven distribution of vehicles among time slots is to adopt a centralized approach for selecting the next relay vehicle. In [23], the protocol proposed aims to classify vehicles into groups and select the relay vehicle with the best line-of-sight of each group. In [21], the Emergency Message Dissemination for Vehicular environments (EMDV) protocol combines both centralized and distributed approaches. In EMDV, the sender determines the next relay vehicle based on neighborhood information received from beacons. The remaining vehicles still follow a delay-based scheme to rebroadcast in case the transmission from the selected vehicle fails. However, one problem arises in centralized approaches when vehicles transmit messages with different power levels, as shown in Figure 1(b). In this scenario,  $v_4$  is the farthest vehicle able to rebroadcast the message received from the sender. However, since  $v_4$  employed a lower power level to send its periodic beacons, the sender could not be aware of  $v_4$ 's presence and mistakenly chooses  $v_3$  as the next relay vehicle. The direct consequence of such mistake is a sub-optimal vehicle selection, leading to higher end-to-end delays. Finally, authors in [18] aim to solve these limitations by letting only the farthest (last) vehicle rebroadcast with The Last One method (TLO). In case the last vehicle fails, after a time threshold the protocol repeatedly defines the next farthest vehicle until the message is successfully broadcasted. Although a distributed approach is used in TLO, authors do not discuss how the threshold value is chosen. In addition, they do not present alternatives for improving end-to-end delay, e.g., by letting more than one vehicle rebroadcast in a single time slot in case of failed transmission or inaccurate positioning information.

### 3. OPTIMIZED TIME SLOT SCHEME

In this work, we tackle drawbacks of current suppression techniques with the **D**istributed **O**ptimized **T**ime (DOT) slot scheme. DOT aims at always selecting the farthest vehicles, i.e., optimal relay vehicles, while controlling transmission redundancy used to increase robustness. To achieve this goal, DOT has the following characteristics:

- **Time slot density control:** it exploits positioning information of 1-hop neighbors to control with precision the time slots' boundaries and, therefore, the number of vehicles assigned to each time slot. This prevents the uneven distribution of vehicles among time slots (Figure 1(a)) when a simple matching of time slots into fixed regions within the transmission range of the sender is used. As a result, transmission redundancy is controlled and end-

to-end delay is kept at a minimum, as there is always a vehicle assigned to the earliest time slot.

- **Distributed:** each vehicle takes the decision regarding when to retransmit a message in a distributed fashion. This prevents sub-optimal selections of a relay vehicle as it can occur with a centralized decision (Figure 1(b)).

### 3.1 Requirements and assumptions

DOT is a suppression scheme that runs on top of the MAC layer, thereby requiring no modification in the de facto standard for vehicular communication IEEE 802.11p.

The scheme relies on the existence of periodic beacons transmitted by each vehicle at a certain rate. These beacons are defined to be transmitted in the form of WAVE Short Messages (WSMs), according to the IEEE 1609 Family of Standards for Wireless Access in Vehicular Environments (WAVE) [27, 26]. The IEEE WAVE standard determines that these messages carry information such as the data rate, channel number and the transmission power level employed. In addition, contextual information about the vicinity is expected to be included, namely, the vehicle's geographical position, speed and acceleration [25]. In this work, we assume that each vehicle is equipped with a device capable of obtaining the current vehicle's geographical position, such as a GPS receiver. Therefore, we consider the following message header structure:  $\langle \text{Vehicle ID}, \text{Message ID}, \text{Time Stamp}, \text{Vehicle's Geographical Coordinates}, \text{Power Level} \rangle$ .

### 3.2 The protocol

By gathering the information contained in beacons, each vehicle keeps a table of one-hop neighbors  $T_n$  containing the latest information about the vicinity. Each entry in  $T_n$  contains the following information:  $\langle \text{Vehicle ID}, \text{Expiration Time}, \text{Vehicle's Geographical Coordinates} \rangle$ . The Expiration Time field is used to remove vehicles from the table that are no longer in the vicinity. Since there may be failures (e.g., collisions) when sending these beacons, we introduce a time tolerance before removing an entry defined as  $t_t = 2.5(\frac{1}{b_f})$ , where  $b_f$  is the beaconing rate, e.g., 10 Hz. This accounts for failure in one beaconing period plus possible extra delay.

The DOT protocol works as follows. Let  $i$  be the vehicle sender of message  $m$ , and  $R$  be the set of vehicles that received  $m$ . Every vehicle  $j \in R$  schedules a rebroadcast for  $m$  with a time delay  $T_{Sij}$ . If any vehicle  $j \in R$  receives an echo of  $m$  before  $T_{Sij}$  expires, it cancels its rebroadcast and ignores future duplicates of  $m$ .

The process for defining  $T_{Sij}$  consists of two main tasks: (i) estimating which vehicles are within the transmission range of the sender and received  $m$ , i.e., belong to set  $R$ ;

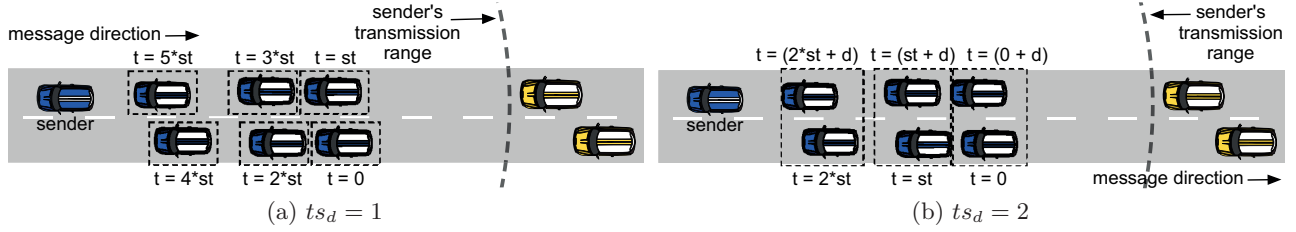


Figure 2: Examples of different settings for the time slot density parameter

and (ii) sorting the entries of every vehicle  $j \in R$  in table  $T_n$  based on its geographical position relatively to the sender. The first task is achieved by using the power level included in  $m$  when transmitted by  $i$ . We elaborate on such estimation in Section 3.3. In the second task, based on the transmission range estimation of the sender, each vehicle receiving  $m$  makes a list  $\vec{v}$  with all its neighbors in  $T_n$  that also belong to set  $R$ . These vehicles are then sorted by their distance relatively to sender  $i$ , where the farthest vehicle is the first element in  $\vec{v}$ . In case different vehicles are equally distant from the sender, they are sorted also by their vehicle ID, where lower ID values are placed in front positions in  $\vec{v}$ .

Figure 3 exemplifies this distributed sorting algorithm. In this example, vehicle  $v_1$  receives a message from the sender and calculates its order among the neighbors in its table  $T_n$  that may also be in the range of the sender, namely, vehicles  $v_0$ ,  $v_2$  and  $v_3$ . With the geographical position of these vehicles in  $T_n$ ,  $v_1$  sorts these vehicles as  $\vec{v} = \langle v_3, v_2, v_1, v_0 \rangle$ .

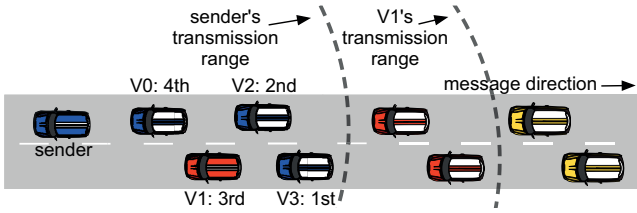


Figure 3: Distributed sorting algorithm

With the sorted list of vehicles  $\vec{v}$ , each vehicle  $j \in R$  finds its own position in  $\vec{v}$ . We denote this position as  $S_{ij} \in [0, n - 1]$ , where  $n$  is the total number of elements in  $\vec{v}$ . Next, the time that vehicles have to wait before rebroadcasting is given by:

$$T_{S_{ij}} = st \left( \left\lceil \frac{(S_{ij} + 1)}{ts_d} \right\rceil - 1 \right) + AD_{ij}, \quad (1)$$

where the main parameter  $ts_d$  determines the number of vehicles that are allowed to be assigned to a single time slot. In other words, this parameter enables the control of time slots' density. The slot time  $st$  is an estimated value of the total time taken for the transmission to complete and the message be fully received by others, accounting for medium access delay, transmission delay and propagation delay.

Assigning different time slots to vehicles clearly helps break the synchronization present in a plain flooding, where all vehicles would rebroadcast nearly simultaneously. However, a similar synchronization on a smaller scale can still occur

when multiple vehicles are assigned to a single time slot. This problem was referred to as the *Timeslot Boundary Synchronization Problem* in [1]. This occurs in our approach when  $ts_d > 1$ . To cope with this problem, we introduce an additional delay  $AD_{ij}$  defined as:

$$AD_{ij} = d(S_{ij} \bmod ts_d), \quad (2)$$

where  $d$  is a time delay sufficiently long for vehicles assigned to the same time slot to sense if other vehicle has already started its transmission, e.g., DIFS in the MAC 802.11p.

Figure 2 shows how our mechanism works when different values for  $ts_d$  are used. With  $ts_d = 1$ , all vehicles in the range of the sender are assigned to individual time slots based on their distance to the sender, as shown in Figure 2(a). Thus, rebroadcasts are separated in time by multiples of slot time  $st$ . In our second example in Figure 2(b),  $ts_d = 2$  is used. In this case, two vehicles are assigned to each time slot. To prevent nearly simultaneous rebroadcasts among the two vehicles in each time slot, the vehicle with higher  $S_{ij}$  value, i.e., nearer to the sender, waits the additional delay  $AD_{ij} = d$ .

With an accurate estimation of set  $R$ , optimal results in terms of transmission redundancy and end-to-end delay are achieved when  $ts_d = 1$ . This leads to the minimum number of rebroadcasts and also to the lowest end-to-end delay, since only optimal relay vehicles, i.e., farthest vehicles from the previous sender, rebroadcast in the earliest time slot. Vehicles assigned to later time slots would cancel their rebroadcasts upon receiving an echo of the message being propagated. However, there are a few factors that can prevent the optimal estimation of set  $R$ , as we discuss in the following section.

### 3.3 Estimating vehicles in the sender's range

As discussed in Section 3, DOT depends on accurately estimating which vehicles are within the transmission range of the sender, i.e., belong to set  $R$ . On the one hand, underestimated transmission range values may lead to an excessive number of vehicles assigned to earlier time slots. This occurs because all vehicles beyond the underestimated range are assigned to the first position in list  $\vec{v}$ . On the other hand, overestimated values may result in longer delays, since vehicles unnecessarily wait for the rebroadcast of other vehicles that actually did not receive any message.

Just as with many vehicles assigned to a single time slot, underestimating the transmission range can lead to multiple vehicles transmitting nearly simultaneously. This may result in collisions and mean the end of a message's dissemination. To prevent this effect, we introduce the following

policy. If a vehicle  $j$  is beyond the range estimated, it is assigned to the last position in list  $\vec{v}$ . If  $\vec{v}$  is empty,  $j$  transmits immediately after a random small delay taken from the interval  $[0, d]$ . This policy may increase the end-to-end delay but it maintains the protocol robust against collisions and contention.

There are two main factors that can affect the estimation of vehicles that belong to set  $R$ : (i) error in positioning information and, thus, inaccurate positioning of vehicles in  $T_n$ ; and (ii) path loss affects in wireless communication such as free-space loss, shadowing, and Doppler effect. While the accuracy of a positioning device such as GPS is generally fixed in the order of a few meters, i.e., 5 meters in outdoor environments [3], in wireless communication the communication range estimation mainly depends on the radio propagation model assumed. Although choosing an appropriate propagation model depends on the current scenario, e.g., if it is urban or a highway, we briefly show in the following how the *outage probability* can be used to estimate the transmission range when the simple log-normal shadowing model is assumed [5]. According to this model, the received power in dB is:

$$[P_r]_{dB} = [P_t]_{dB} + K_{dB} - 10\gamma \log_{10}(d/d_0) - \psi_{dB}, \quad (3)$$

where  $P_r$  is the received power at distance  $d$ ;  $P_t$  is the transmit power (included in the sender's message);  $K_{dB}$  is the unit power loss in dB which depends on the antenna properties of the transceivers;  $\gamma$  is the path loss coefficient which depends on the radio environment;  $d_0$  is the reference distance;  $\psi_{dB}$  is a Gauss distributed random variable with zero mean and with  $\sigma_{\psi_{dB}}^2$  as the variance generated due to the shadowing effect. We consider the channel as either slow fading or as very fast fading. Slow fading and very fast fading channels have almost the same performance as additive white Gaussian noise (AWGN) channels. To analyze the performance of wireless communication in AWGN we have to consider two criteria of interest: the bit error probability and the outage probability. In AWGN, for the BPSK modulation the bit error probability is defined as:

$$P_b = Q\left(\sqrt{2\gamma_0}\right). \quad (4)$$

The outage probability  $P_{out}$  is the probability that the received signal's average SNR  $\bar{\gamma}_s$  falls below the minimum required SNR for the pre-defined acceptable communication performance  $\gamma_0$  [5, 7]. Mathematically,

$$P_{out} = p(\bar{\gamma}_s < \gamma_0) = \int_0^{\gamma_0} p_{\gamma_0}(\gamma) d\gamma. \quad (5)$$

From Equations 4 & 5 the required average SNR is:

$$\bar{\gamma}_s = \frac{(Q^{-1}(P_b))^2}{-2\ln(1 - P_{out})}. \quad (6)$$

In AWGN, the carrier-to-noise ratio of the received signal is:

$$\left(\frac{C}{N}\right)_{dB} = \left[\frac{E_b}{N_0}\right]_{dB} + \left[\frac{f_b}{B}\right]_{dB}, \quad (7)$$

where  $\frac{E_b}{N_0} = \bar{\gamma}_b$  is SNR per bit;  $f_b$  is the channel data rate (net bitrate); and  $B$  is the channel bandwidth [5]. As  $C_{dB} = 10 \log(P_r)$  and for the BPSK modulation  $\bar{\gamma}_b = \bar{\gamma}_s$ , Equation 7 can be re-written as:

$$[P_r]_{dB} = [\bar{\gamma}_s]_{dB} + \left[\frac{f_b}{B}\right]_{dB} + N_{dB} \quad (8)$$

Finally, using Equations 3,6 & 8 the transmission range can be estimated by:

$$d = d_0 \times 10^{\frac{[P_t]_{dB} + K_{dB} - \left[\frac{(Q^{-1}(P_b))^2}{-2\ln(1 - P_{out})}\right]_{dB} - \left[\frac{f_b}{B}\right]_{dB} - N_{dB}}{10\gamma}} \quad (9)$$

In wireless transceiver design, a typical BER of  $10^{-4}$  and 2% outage probability are considered acceptable in performance. Figure 4 shows estimated transmission range values for increasing outage probabilities. In this work, we assume in our simulation, transmission range values with 2% of outage probability. Thus, values are approximately 100, 150, 200 and 300 meters for power values of 300, 800, 2800 and 10000 mW, respectively.

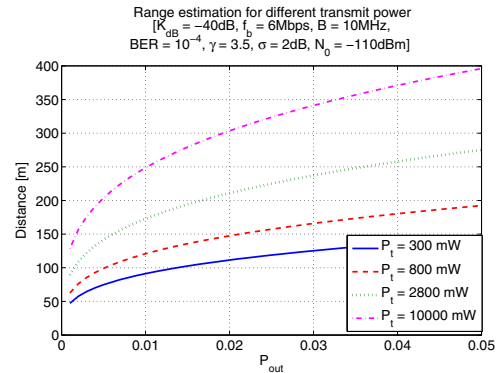


Figure 4: Transmission range estimation for increasing accepted outage probabilities and power levels.

## 4. PERFORMANCE EVALUATION

The performance evaluation of DOT is carried out by means of simulations. Our goal is to study the scalability of DOT under diverse scenarios by comparing it with two state-of-the-art suppression techniques, namely:

- **Slotted 1-Persistence**: it is the mechanism that achieved best performance in terms of end-to-end delay among the two slotted schemes proposed in [29].
- **Optimized Slotted 1-Persistence**: it relies on an optimized version of the Slotted 1-Persistence suppression method to prevent nearly simultaneous rebroadcasts in a single time slot in dense networks [16].

We utilize the MiXiM Framework<sup>1</sup> and adjust the available implementation of the IEEE 802.11b protocol to comply

<sup>1</sup><http://mixim.sourceforge.net>

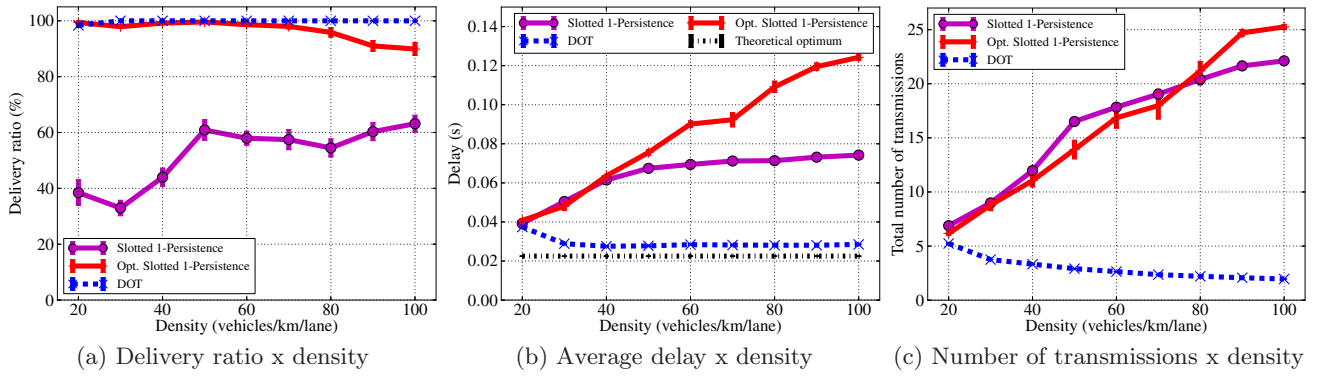


Figure 5: Results with 95% confidence intervals for increasing network densities

with basic specifications of the 802.11p version. Table 1 contains a summary of the simulation parameters. In the MAC layer, we set the bit rate to 6 Mbit/s, the Contention Window (CW) to values between 15 and 1023, the slot time to 13  $\mu$ s, the SIFS to 32  $\mu$ s, and the DIFS to 58  $\mu$ s. In the physical layer, we operate on the 5.9 GHz frequency band, with 10 MHz of bandwidth. Based on our estimates in Section 3.3, we set the transmission power to 800 mW to achieve approximately 150 meters of communication range with outage probability of 2%. We use the Friis Free Space Path Loss (FSPL) propagation model with exponent  $\alpha$  equal to 3.5, as it is within the range 2.7 to 5, estimated for outdoor shadowed urban areas in [15]. In addition, we include shadowing effects that are modeled following a log-normal distribution with zero mean and standard deviation  $\sigma = 6.25$  dB, as it is within the range 4 to 12 dB for outdoor propagation conditions according to [15]. The modulation used is the one provided by the Veins project<sup>2</sup>, which is based on measurements from [17] for the 6 Mbit/s bitrate.

For all suppression mechanisms, we set the slot time  $st$  to 5 ms. We define the total number of time slots for Slotted 1-Persistence  $NS_{std}$  to 3 and for Optimized Slotted 1-Persistence we set  $NS_{opt}$  to 6 (3 slots for each road direction as defined in [16]). The value chosen for Slotted 1-Persistence is based on simulation parameters used in [20]. The maximum additional delay  $D_{max}$  used by Optimized Slotted 1-Persistence is set to 1 ms. Finally, for the DOT mechanism we set the time slot density  $ts_d$  to 1 and additional delay  $d$  to DIFS.

For all simulation scenarios the message size is 2312 bytes large, the maximum allowed by the 802.11p standard. Data messages are generated every 2 seconds, i.e., message frequency of 0.5 Hz. Each message is generated by one fixed vehicle positioned in one end of the road and gathered by another fixed vehicle in the other end of road. For each simulation scenario 20 runs of 100 seconds are executed. Finally, beacons are 24 bytes large and sent at 1 Hz. The choice for such beaconing rate is based on the fact that vehicles move in the simulation only once per second. Therefore, neighbors' information would not be improved with a higher beaconing rate. Furthermore, varying the beaconing rate in early experiments has not led to significant changes in our simulation results.

Physical Layer	Frequency Band	5.9 GHz
	Bandwidth	10 MHz
	Transmission Range	$\sim 150$ m
	FSPL exponent $\alpha$	3.5
	Log-normal $\sigma$	6.25 dB
	Modulation	Based on [17]
Link Layer	Bit Rate	6 Mbit/s
	CW	[15,1023]
	Slot Time	13 $\mu$ s
	SIFS	32 $\mu$ s
	DIFS	58 $\mu$ s
Suppression Mechanisms	$st$	5 ms
	$ts_d$	1
	$d$	DIFS
	$NS_{std}$	3
	$NS_{opt}$	6
	$D_{max}$	1 ms
	Beacon Size	24 Bytes
Scenarios	Beacon Frequency	1Hz
	Data Message Size	2312 Bytes
	Data Message Freq.	0.5 Hz
	Network Density	50 veh./km/lane
	# Runs	20

Table 1: Simulation parameters

We consider a scenario with a 1-kilometer straight highway with two lanes in each road direction. This scenario was created with SUMO [9]. Therefore, it includes realistic mobility patterns such as vehicle overtaking, lane changing, and relies on the well-known car-following mobility model. Vehicles' speeds vary according to the density considered by following the Krauß mobility model, i.e., the higher the density is, the slower vehicles move.

Our evaluation considers the following metrics:

- **Delivery ratio:** the percentage of messages generated by the farthest vehicle in one end of the road which fully propagate and are received by a vehicle in the extreme opposite end of the road. Ideally, dissemination protocols must achieve a delivery ratio percentage close to 100% in dense networks.
- **Delay:** the total time taken for a message to propagate from one end to the other of the road length. This is particularly important for critical safety messages that must be disseminated as quickly as possible. We additionally compare the performance of each protocol with a theoretical optimum which serves as lower bound. This value is

<sup>2</sup><http://veins.car2x.org/>

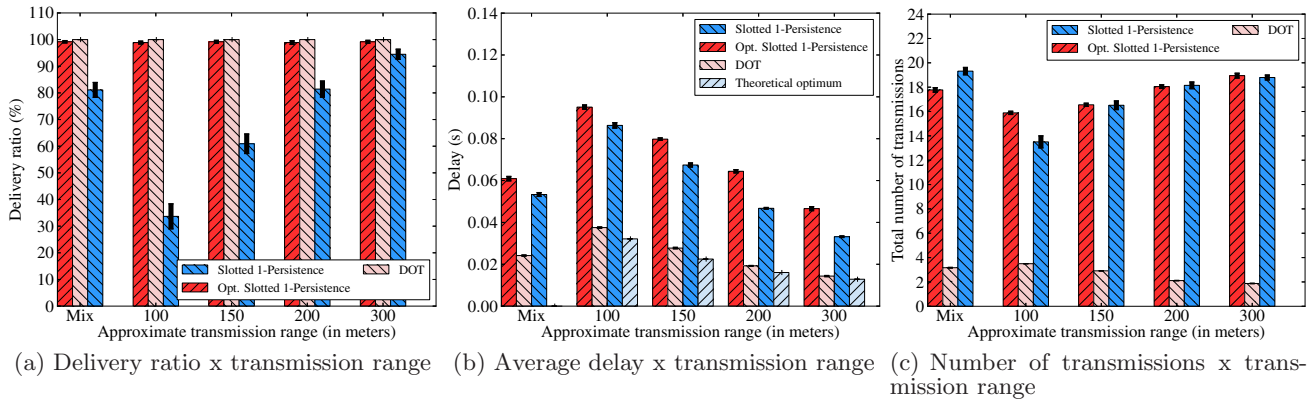


Figure 6: Results with 95% confidence intervals for different transmission range settings

simply calculated as the minimum number of hops that a message must travel times the transmission delay, given the transmission range employed.

- **Total number of transmissions:** the total number of transmissions performed on average by an arbitrary vehicle. We consider only data messages in these results, thereby excluding transmissions of beacons. This value is normalized by the total number of vehicles in each scenario. In order to be scalable, protocols must keep a low number of transmissions during a message’s dissemination.

#### 4.1 Network density

We first study the performance of the protocols with increasing network densities. Since we focus on dense networks, we fix the parameters in Table 1 and vary the density from 20 to 100 vehicles/km/lane.

As shown in Figure 5(a), Slotted 1-Persistence improves its delivery ratio up to 60% as the network density increases. This is explained by the extra rebroadcast redundancy which occurs when more vehicles are assigned to a single time slot. In contrast, DOT maintains performance of near 100% for all density values, whereas Optimized Slotted 1-Persistence reaches 100% up to density of 60 vehicles/km/lane and suffers a decrease of up to 10% with density of 100 vehicles/km/lane.

Figure 5(b) shows the performance with respect to the end-to-end delay. The end-to-end delay tends to increase with density for protocols that rely on a fixed number of time slots such as Slotted 1-Persistence and Optimized Slotted 1-Persistence. This can be reasoned by the higher contention delay generated when more vehicles attempt to rebroadcast in a single time slot. In contrast, DOT scales properly with increasing densities. In fact, the higher the density of the network, the higher the chance is that a vehicle is positioned closer to the border of the transmission range. Thus, delay values with DOT are close to the theoretical optimum in densities ranging from 30 to 100 vehicles/km/lane.

The number of transmissions performed by Slotted 1-Persistence and Optimized Slotted 1-Persistence also increases with higher densities, as shown in Figure 5(c). This is due to the higher number of vehicles positioned in the geographical region corresponding to a single time slot. By relying on the control of time slot density, DOT scales properly with higher densities. In fact, in proportion with the

total number vehicles in each density, the number of transmissions tends to decrease.

In general, DOT scales more efficiently with increasing network densities when compared with traditional methods that employ fixed time slots such as Slotted 1-Persistence and Optimized Slotted 1-Persistence.

#### 4.2 Transmission range

Another important aspect is the performance of protocols when different transmission ranges are employed by vehicles. Specially for approaches that employ a fixed number of time slots, increasing the transmission range affects directly the size of each time slot and, thus, the performance of protocols. In addition, it affects the number of hops required for a message to travel the complete highway considered. We fix the parameters in Table 1 and vary the transmission range from 100 to 300 meters. Additionally, we consider the scenario *mix* where different vehicles employ different transmission ranges. More specifically, each of the ranges 100, 150, 200 and 300 meters is used by 25% of the vehicles. Each vehicle takes a range value in the beginning of the simulation run and employ it until the simulation ends.

Figure 6(a) shows the performance of protocols with respect to the delivery ratio. Both Optimized Slotted 1-Persistence and DOT protocols achieve near 100% in every transmission range setting. In contrast, Slotted 1-Persistence shows higher delivery ratio when considering higher transmission range values. This is explained by the extra rebroadcast redundancy and fewer hops needed for a message to be fully disseminated when higher transmission ranges are employed. Furthermore, Slotted 1-Persistence is affected when different ranges are employed by different vehicles, which can also be explained by the higher number of hops required on average for a message’s dissemination.

With fewer hops needed for a message to travel, the end-to-end delay presented by each protocol also decreases when higher transmission ranges are employed (Figure 6(b)). DOT presents the lowest delay, with values near the theoretical optimum for each range setting.

Figure 6(c) shows the total number of transmissions performed by each protocol. Since Slotted 1-Persistence and Optimized Slotted 1-Persistence adopt a fixed time slot approach, higher transmission ranges means more vehicles assigned to a single time slot. Therefore, more rebroadcast

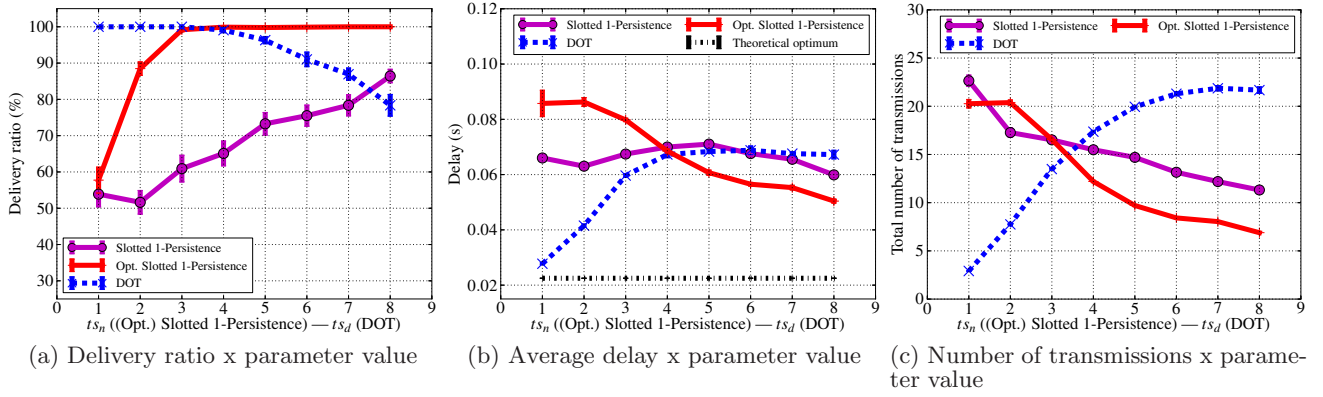


Figure 7: Results with 95% confidence intervals for different time slot parameters used by each protocol

redundancy and thus more transmissions are expected. On the other hand, DOT controls the time slot density regardless of the current density of vehicles within the transmission range. Therefore, fewer hops is translated to fewer transmissions.

Results show that not only DOT scales properly with increasing and heterogeneous transmission range settings, but also achieves near optimum performance in terms of end-to-end delay.

### 4.3 Time slot parameter

In this section, we analyze the performance of protocols when varying their main parameters, namely, the total number of time slots  $ts_n$  (used by Slotted 1-Persistence and Optimized Slotted 1-Persistence) and the time slot density  $ts_d$  (used by DOT). Other parameters are fixed as shown in Table 1. In particular, Optimized Slotted 1-Persistence uses doubled values of  $ts_n$  to distribute the number of time slots equally among the two road directions, as detailed in [16].

With regard to the delivery ratio, both Optimized Slotted 1-Persistence and Slotted 1-Persistence achieve higher delivery ratio when increasing the total number of time slots, as shown in Figure 7(a). In fact, employing more time slots leads to a lower number of vehicles assigned to a single time slot. Therefore, a lower level of rebroadcast redundancy is expected and messages can travel with less interference throughout the road length. The opposite effect occurs when the time slot density is increased in DOT. Higher values for  $ts_d$  means more vehicles within a single time slot, which leads to a decrease in delivery ratio from  $ts_d = 4$  in this scenario.

Equivalently to what occurs when varying the network density, there is an increase in delay when more vehicles attempt to transmit nearly simultaneously in a single time slot (Figure 7(b)). This occurs when decreasing  $ts_n$  (Optimized Slotted 1-Persistence and Slotted 1-Persistence) or increasing  $ts_d$  (DOT). Such increase in the number of transmissions can be confirmed in Figure 7(c). In general, the increase in delay is upper bounded by the network density in the scenario considered, which consequently limits the maximum number of vehicles that are within the transmission range of 150 meters.

In general, all protocols perform best when fewer vehicles attempt to transmit nearly simultaneously. This means

$ts_d = 1$  for DOT and  $ts_n = 8$  for Optimized Slotted 1-Persistence and Slotted 1-Persistence. However, while finding the optimal value for  $ts_n$  in Optimized Slotted 1-Persistence and Slotted 1-Persistence depends on accurately knowing the current network density, DOT with  $ts_d = 1$  scales independently from other factors.

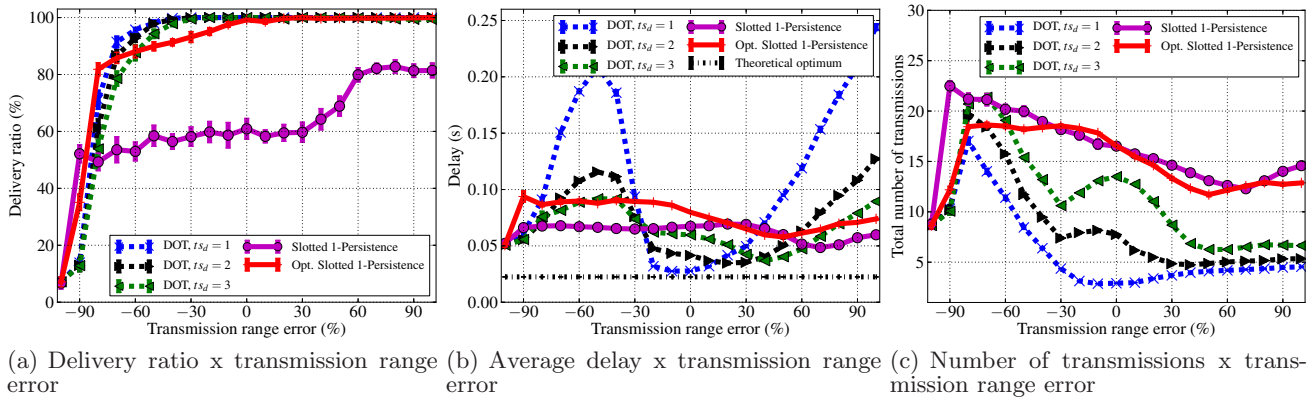
### 4.4 Transmission range error

All protocols considered in our evaluation depend on accurately estimating which vehicles are within the sender's transmission range in order to distribute time slots among vehicles efficiently. As discussed in Section 3.3, due to a certain error probability in the wireless communication and inaccurate positioning estimation (GPS), the transmission range might be either underestimated or overestimated. Thus, we study the effects of such errors on the performance of each protocol. With an outage probability of 2%, the central point zero in the x-axis represents an accurate estimation of the transmission range, which is approximately 150 meters. Negative and positive values in the x-axis are underestimated and overestimated percentage values with respect to point zero, respectively. Other parameters are fixed as shown in Table 1. We additionally consider results of running DOT with  $ts_d = 2$  and  $ts_d = 3$ .

Figure 8(a) shows the performance of protocols with respect to the delivery ratio. For all protocols, an inaccurate transmission range estimation may result in vehicles being assigned to a sub-optimal time slot. Nevertheless, every vehicle still schedules a rebroadcast, which helps prevent the dissemination of messages from being stopped. When the transmission range is underestimated, time slots are mapped to smaller geographical regions. However, vehicles positioned beyond the underestimated range still receive and rebroadcast messages. This leads to a high level of transmission redundancy in a single time slot and, thus, to a lower delivery ratio down to 5% when the complete range is underestimated.

The results with respect to the end-to-end delay are shown in Figure 8(b). For protocols relying on fixed time slots such as Optimized Slotted 1-Persistence and Slotted 1-Persistence, changing the boundary of the time slots does not considerably affect the expected end-to-end delay. With a density of 50 vehicles/km/lane used in this scenario, the chance that at least one vehicle is positioned in the geographical region





**Figure 8: Results with 95% confidence intervals for increasing underestimation and overestimation errors in the transmission range estimation**

mapping the earliest time slot is high. One variation that can be observed in these protocols is with regard to the number of transmissions (Figure 8(c)). With underestimated range values, more vehicles positioned beyond the underestimated range are assigned to the earliest time slot, thereby resulting in more transmissions.

In contrast, inaccurate range estimations directly affect the expected end-to-end delay in DOT. As discussed in Section 3.3, to prevent an increase in number of transmissions when the transmission range is underestimated, vehicles positioned beyond the estimated range border are placed in the back of the sorted list  $\vec{v}$ . This results in increasing the end-to-end delay, as all vehicles will rely on such underestimated range and, thus, more hops will be needed for a message to be fully disseminated along the road. For underestimated values higher than 60%, the end-to-end delay starts to decrease as a consequence of the lower delivery ratio present in this range for all protocols. On the other hand, higher delay values can also be expected with an overestimation of the transmission range, since vehicles may unnecessarily expect other vehicles farther in the message direction to rebroadcast. When more vehicles are assigned to a single time slot, i.e.,  $ts_d > 1$ , both effects can be minimized as shown in Figure 8(b). This is explained by the higher chance that an inaccurate estimation is compensated by another vehicle also assigned to the same time slot but positioned farther or nearer the sender. Although the number of transmissions also increases with higher underestimated ranges, the values achieved are considerably lower when compared with Optimized Slotted 1-Persistence and Slotted 1-Persistence as shown in Figure 8(c).

Results show that overestimating values for the transmission range is less harmful for all protocols with regard to delivery ratio and number of transmissions. For all levels of estimation errors, DOT presents better performance results with regard to delivery ratio and number of transmissions. Despite the effects of inaccurate range estimations, DOT still presents lower end-to-end delay values compared with Optimized Slotted 1-Persistence and Slotted 1-Persistence considering a range of error up to 30%. Nevertheless, these effects are minimized when higher time slot density values are allowed.

## 5. CONCLUSION AND FUTURE WORK

In this paper, we have presented a broadcast suppression scheme that is scalable to diverse network densities. We addressed major problems in current delay-based techniques and designed the **D**istributed **O**ptimized **T**ime (DOT) slot scheme. By exploiting the presence of 1-hop neighbor information contained in periodic safety beacons, DOT is capable of controlling with high precision the density of vehicles within each time slot. By means of simulations, we showed that DOT is scalable, achieves near optimum delay results, and is robust to errors caused by possible inaccurate transmission range estimations. Furthermore, DOT outperformed other delay-based schemes in diverse network densities. In future work, we will aim to incorporate DOT in a store-carry-forward scheme which is suitable for both highway and urban scenarios.

## 6. ACKNOWLEDGMENTS

This work is supported by iLAND Project, ARTEMIS-2008-1, Project contract no. 100026; and by SI<sup>4</sup>MS project NWO/STW grant (dossier 655.010.209).

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