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Geographic scheduling of directional transmission for periodic safety messages in IEEE WAVE

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ABSTRACT

It is typically assumed that safety communication will use omnidirectional broadcast in vehicle-to-vehicle environments. However, in the IEEE Wireless Access in Vehicular Environment standard, some safety application messages will have directional semantics. For example, messages in the cooperative adaptive cruise control application are relevant to vehicles following the transmitter. In this paper, we investigate the impacts of using directional communication that is tailored to such applications. In particular, we show that the directional transmission indeed improves the message delivery probability by reducing message spillover in unnecessary directions. However, we also find that such benefit is not automatically obtained. Analysis reveals that it is crucial that the temporal ordering of the transmission is aligned with the vehicles' spatial ordering to minimize the hidden terminal losses and fully garner the benefits of directional communication. For a method to ensure that the alignment takes place, we propose an application-level message scheduling solution that utilizes vehicle position information, and demonstrate that it leads to both lower channel utilization and higher message delivery rates than omnidirectional transmission.

1. Introduction

In Institute of Electrical and Electronics Engineers (IEEE) Wireless Access in Vehicular Environment (WAVE) systems [1–3], periodically transmitted beacons[1] (*e.g.* Basic Safety Messages (BSMs) [4]) broadcast from each vehicle are vital to create cooperative neighborhood awareness. These BSMs report the vehicle's position, speed, and direction among other values [5]. They enable driving safety applications such as cooperative collision warning (CCW) [6], and provide the basis for topology construction and multi-hop message routing [7]. Therefore, the reliable and efficient delivery of the beacon messages is essential to improve driving safety and facilitate vehicular network robustness and agility.

One difficulty in the reliable delivery of the beacon is channel congestion, which occurs when the IEEE 802.11p channel capacity allocated for the beacon exchange is exceeded because of the density of vehicular traffic. For instance, if the beacon is transmitted at 6 Mbps and the beacon size is 300 bytes, the channel cannot accommodate more than 2500 beacons per second. At 10 Hz frequency, this means that a maximum of 250 vehicles can be within the mutual communication range. However, because of the randomness of the transmission, congestion and consequent message collision losses occur at much lower traffic densities.

Under the IEEE WAVE standard, many safety applications will rely on omnidirectional communications. However, some will surely have directional semantics. For example, messages in the cooperative adaptive cruise control (CACC) application [4,8] are relevant to vehicles following the transmitter. Thus, it is necessary to investigate *how the congestion control problem differs in directional communication and how we should deal with it*. In this paper, we focus on measuring the utility of directional transmission in terms of the message delivery probability by reducing message spillover in unnecessary directions. Minimizing channel usage by periodic beacons is important, as the channel will be freed up for other applications. In particular, the European standard is more explicit about this requirement. European Telecommunications Standards Institute (ETSI) TS 102 687 stipulates that the congestion control should "keep channel load caused by periodic messages below pre-defined thresholds" and "reserve communication resources for the dissemination of event-driven, high-priority messages" [9].

In this paper, we investigate the impacts of using directional communication that is tailored to the applications that have directional semantics. In particular, we show that the directional transmission indeed improves the message delivery probability by reducing message spillover in the unnecessary directions. However, we also find

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[1] Throughout this paper, we will use the terms BSM and "beacon" interchangeably. Note that this safety beacon, a periodic application message, is different to the IEEE 802.11 beacon, which is a management message for wireless Local Area Networks (LANs).

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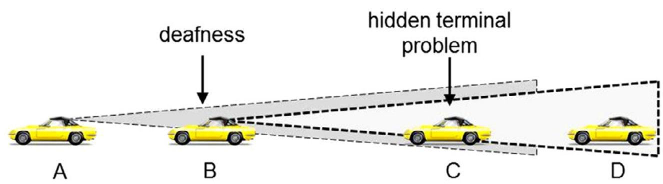


Fig. 1. MAC problems in directional beacon transmissions (B is the reference transmitter).

that such benefit is not automatically obtained. Through analysis, we show that it is crucial that the temporal ordering of the transmission is aligned with the vehicles' spatial ordering in order to minimize the hidden terminal losses and fully garner the benefits of directional communication. For a method to ensure that the alignment takes place, we propose an application-level message scheduling solution that utilizes vehicle position information. Moreover, we show that the scheduling decision can be made by the application that uses the directional semantics. By utilizing the vehicle position information in the safety messages, vehicles within the mutual communication range can determine their relative order in the transmission schedule. In this paper, we will demonstrate that this approach leads to both lower channel utilization and a higher message delivery rate than omnidirectional transmission.

Previous research has explored the idea of using directional communication from a moving vehicle [10] or a mobile terminal [11], whereby the antenna is aimed at the proper access point or a roadside unit (RSU) in order to extend the connection time or improve the channel quality. In this paper, however, we attempt to employ this idea in the vehicle-to-vehicle (V2V) context. To the best of our knowledge, this paper is the first to tackle the hidden terminal problem for directionally broadcast safety messages through application layer scheduling. Note that the proposed scheme is not designed to replace existing congestion control approaches such as rate control and power control. Because our scheme is orthogonal to them, they can be used in parallel.

2. Problem definition

It is well known that the use of directional antennas aggravates the hidden terminal problem on the Medium Access Control (MAC) layer in ad hoc and (in particular) vehicular networks [12]. For example, suppose that vehicle B in Fig. 1 is directionally transmitting its beacon to the following vehicles for CACC. Because vehicle A cannot hear B's transmission, it may transmit its beacon as well. As a result, the beacons may collide at vehicle C, which both A and B can reach, and C may fail to correctly decode either beacon. In this paper, we show that this MAC layer problem can be solved in the application layer by the beaconing applications themselves.

In this paper, the hidden terminals for a reference transmitter r in both directional and omnidirectional communication are defined to be the vehicles that

1. can reach some of r's receivers in their transmission range,
2. cannot sense r's transmission.

For example, in Fig. 1, A can reach B's receivers but cannot hear B's directional transmission, so A is a hidden terminal for B. On the other hand, B is deaf to A's transmission if it commences transmission before A.

2.1. Impact of the hidden terminal problem in vehicular communication

To quantify the impact of the aggravated hidden terminal problem in directional transmission, we first conduct simulation experiments using the Qualnet 5.1 simulator. Table 1 summarizes the parameters

Table 1
Simulation settings for comparison.

Parameter		Value
Channel	Frequency band	5.9 GHz
	Path loss	Free space (<556 m)
		2-ray ground (>556 m)
	Shadowing	Constant (mean = 4.0)
	Fading	Rician ($K = 3$)
PHY	Directional beam width	35°
	Tx power	20 dBm (e.i.r.p.)
		3.15 dBm (e.i.r.p.)
	Rx sensitivity	−85 dBm
	Protocol	802.11p
	Data rate	6 Mbps
	Channel bandwidth	10 MHz
	Capture effect	Enabled
MAC	Protocol	802.11p + 1609.4
	Channel usage	Continuous
	CW_{min}	3
Application	Beacon size	200 bytes
	Messaging frequency	25 Hz
Vehicular	Road topology	5-km-long 1-lane road
	Inter-vehicle distance	5–30 m per lane
	Mobility model	Static/car-following
	Vehicle speed	[10, 15, 20] m/s

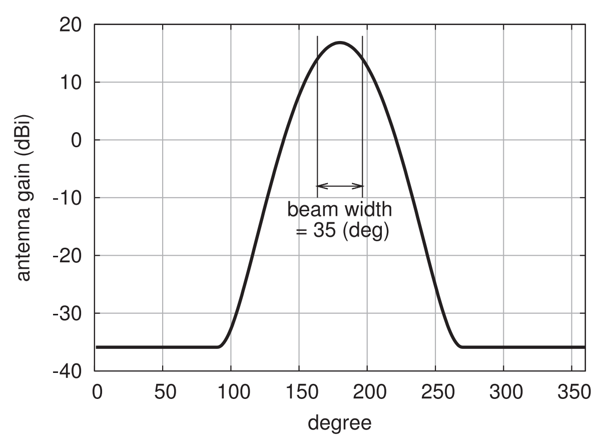
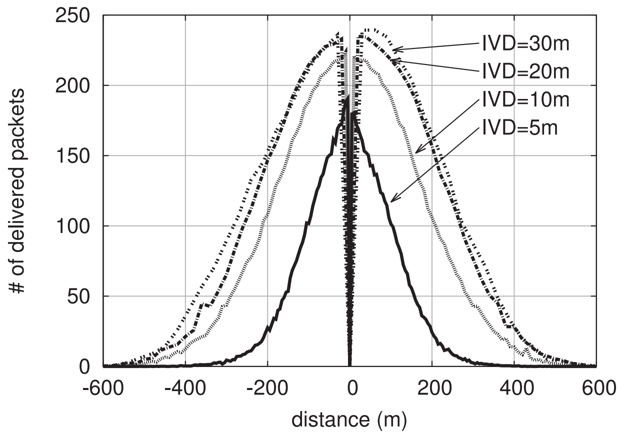
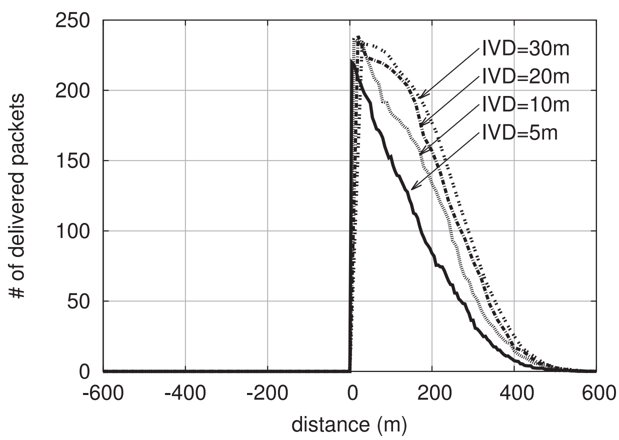


Fig. 2. Antenna pattern in directional transmission.

used in the simulation experiments. The Qualnet simulator models the channel as having free space path loss up to a certain distance d_{break}, beyond which the channel is modeled by the 2-way ground model. In this paper, we model the height of the vehicle antennas to be 1.5 m above the ground, which makes d_{break} 556 m. The channel also experiences Rician fading, with $K = 3$. With regard to the 2-way ground model, a perfect electric conductor is assumed. The omnidirectional Tx power is set to 20 dBm (e.i.r.p.), where the antenna gain is 0 dBi. For directional transmission, the beam width is 35°, and the Tx power is set to 3.15 dBm. Because the peak antenna gain in the direction of the main lobe is set to 16.85 dBi, however, this amounts to 20 dBm (e.i.r.p.). The antenna pattern has been generated using the Dolph–Chebyshev method, and is shown in Fig. 2. The gains in 0–90° and 270–360° are limited to −35.90 dBi. Given this pattern, when a vehicle transmits, the front vehicle (which the back lobe reaches) at the minimum distance of 5 m (considering typical vehicle lengths) is less than −85 dBm, the Rx sensitivity. Therefore, the front vehicle will not be able to sense the signal, and the MAC protocol behavior of the front vehicle will continue as if it has not heard the transmission. Throughout this paper, we assume that the transceiver operates in half-duplex mode, as the vast majority of today's wireless transceivers are half-duplex, although full-duplex wireless communication technology has recently been realized [13]. The channel width is 10 MHz, following the IEEE 802.11p specification.

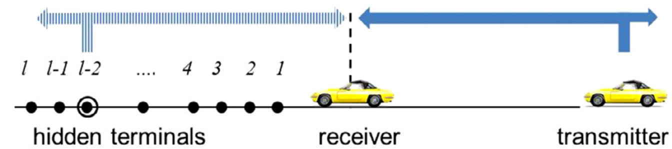


(a) Omnidirectional transmission

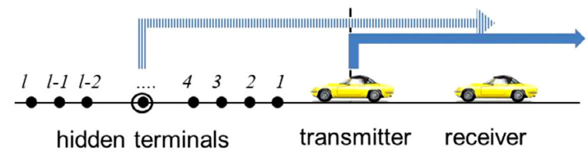


(b) Directional transmission

Fig. 3. Packet delivery with and without directional communication.



(a) Omnidirectional



(b) Directional

Fig. 4. Worst-case locations of the hidden terminal problem differ for omnidirectional and directional communication.

The simulator correctly reflects the channel width on the noise floor computation.

The beacon transmission rate is set to 6 Mbps [14], and each beacon payload is 200 bytes in size. We vary the vehicle traffic density in the form of the inter-vehicle distance (IVD) from 5 m(/lane) to 30 m(/lane), where the IVD is defined to be the distance between the identical positions (*e.g.* centers) of consecutive vehicles. These high traffic densities are used to create message congestion on the Dedicated Short-Range Communications (DSRC) channel. In particular, IVD = 5 m is practically the worst-case scenario, with vehicles lined up bumper to bumper, as the typical car length is around 5 m, although trucks and buses are even longer. In the mobility scenario, vehicles move according to the car-following model. The vehicle speeds are either 10, 15, or 20 m/s depending on the lane. The beacon generation frequency is 25 Hz, as in the CACC application [15]. Of the four channel usage modes in the IEEE 1609.4 standard [3], we assume the continuous mode, because most vehicles will be equipped with dual radio. Finally, the performance metric is the number of successfully delivered packets as a function of the distance of the receiver from the reference vehicle.

In Fig. 3, we can observe the degree to which directional transmission improves the message delivery probability by aiming the messages in the application-required direction. The simulation corresponds to 10 wall clock seconds, so a total of 250 beacons were transmitted by the reference vehicle. The figures show the average number of beacons of the 250 transmitted by the reference vehicle that were successfully received by other vehicles at different distances. The horizontal axis gives the distance of the receivers from the reference vehicle, and the vertical axis shows the number of successfully delivered beacons. First, Fig. 3(a) shows the case of omnidirectional communication. As the vehicular traffic density increases (*i.e.*, as the IVD decreases), the packet delivery probability naturally decreases due to collisions and interference from hidden terminals. For instance, with IVD = 5 m, only 70% of the beacons are delivered even at the closest transmitter proximity.

Fig. 3(b) shows the impact of employing directional transmission (toward the traffic upstream; see Fig. 1). Surprisingly, there was only a marginal improvement, except for IVD = 5 m. In other traffic densities, directional transmission performs only comparably or even worse than the omnidirectional case (*e.g.*, for short distances with IVD = 30 m). This is a disappointing result, because directional transmission eliminates at least 50% of the beacon traffic from the channel. In the next section, we show that this is due to the aggravated hidden terminal problem. This result clearly confirms that using directional communication alone does not automatically improve the packet delivery rate.

2.2. Worst-case analysis

The marginal utility of directional communication for messages with directional semantics largely arises from the intensified hidden terminal problem. To understand this aspect, we analyze the worst-case scenario. That is, we count the number of active hidden terminals at the position where the most hidden terminals can affect the intended receiver of a message from the reference vehicle.

For the analysis, we assume that vehicles are uniformly distributed along a one-dimensional road topology. The vehicles become directional when they transmit messages having directional semantics, whereas they remain omnidirectional for reception, because messages may be transmitted by other (possibly omnidirectional) applications. In both omnidirectional and directional communication scenarios, the average number of potential hidden terminals for the aforementioned worst-positioned receiver is the same, and will be shown to be $N/2$, where N is the number of vehicles within communication range. However, the number of hidden terminals among the $N/2$ that actually affect a given receiver differs in the two scenarios.

In Fig. 4, we show the worst-case positions with omnidirectional and directional transmissions. For omnidirectional transmission (Fig. 4(a)), the worst-case interference from the hidden terminals occurs at the farthest fringe of the reference vehicles' transmission coverage. There, the reference transmitter's power is the lowest, whereas the number of hidden terminals that can affect a receiver is the highest. In contrast, as the receiver becomes

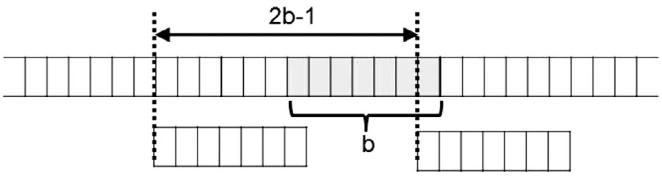


Fig. 5. $2b-1$ starting times that lead to overlap with reference vehicle transmission.

closer to the transmitter, fewer hidden terminals affect the receiver. For directional transmission, the worst-case interference from the hidden terminals takes place just behind the reference transmitter, because the hidden terminals are in the opposite direction to the transmission. The farther upstream the receivers are from the reference vehicle, the fewer hidden terminals can reach them (Fig. 4(b)). From the figure, it is evident that the average number of hidden terminals for the worst-positioned receiver is $\frac{N}{2}$ for both the directional and omnidirectional cases.

Let us now suppose that vehicles transmit beacons at frequency f. Let $I = 1/f$ be the transmission period. Then, there are I/c contention slots in a period, where c is the length of the 802.11p contention slot. Assuming that vehicles are uniformly distributed in terms of the beacon transmission time, the probability that a vehicle starts its beacon transmission in a given contention slot is $x = c/I$. Below, we compute the probability that the transmission from the reference vehicle collides with another transmission from a hidden terminal.

1. **Omnidirectional transmission**: For $k \geq 1$ hidden terminals to interfere with the transmission from the reference vehicle, the k terminals must start simultaneously. This is because, if one starts earlier, no other hidden terminals can transmit in the sensing range of the first transmitting hidden terminal. Suppose the starting time of the k simultaneous hidden transmissions is the slot $i \geq 1$. That is, the first $(i-1)$ slots are left idle by the k interfering terminals, whereas all i slots are left idle by the other $N/2-k$ hidden terminals not transmitting at this time. Because the probability that a vehicle leaves a given slot idle is $(1-x)$, the probability that k out of $\frac{N}{2}$ potential hidden terminals concurrently transmit beacons exactly at slot i is given by

$$P_{\mathrm{HO}}^{(i)}[k] = \binom{\frac{N}{2}}{k}\{(1-x)^{i-1}x\}^{k}\{(1-x)^{i}\}^{\frac{N}{2}-k}.$$

Now, given the k simultaneously starting hidden terminals, how many starting positions i can overlap with the reference transmission? Suppose the length of a message is b slots. In Fig. 5, the b shaded slots depict the beacon transmission from the reference vehicle. By definition, the hidden terminals cannot sense the reference transmission, and can transmit anywhere on the time axis. The *actual* overlapping transmission that affects the reference transmission should be in the $2b-1$ interval, as depicted in Fig. 5. For each starting position i in the interval, k simultaneously starting hidden terminals can appear. The probability that k hidden terminals out of $\frac{N}{2}$ concurrently transmit beacons while the transmission from the reference vehicle is under way is given by

$$P_{\mathrm{HO}}[k] = \sum_{i=1}^{2b-1} P_{\mathrm{HO}}^{(i)}[k] = \sum_{i=1}^{2b-1}\binom{\frac{N}{2}}{k}\{(1-x)^{i-1}x\}^{k}\{(1-x)^{i}\}^{\frac{N}{2}-k}. \quad (1)$$

Finally, it is evident that the probability of no hidden terminals transmitting during the vulnerable period of $2b-1$ slots is given by

$$P_{n\mathrm{HO}} = (1-x)^{\frac{N}{2}(2b-1)}.$$

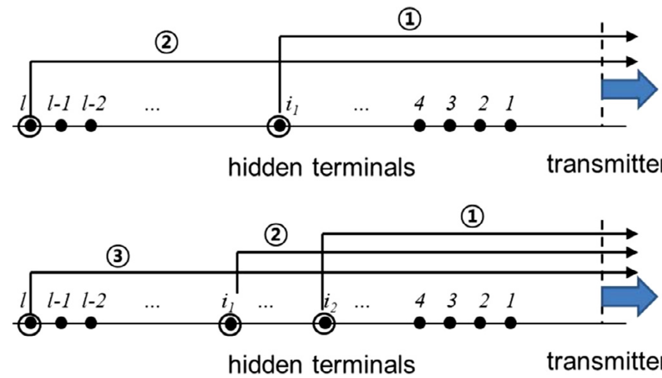


Fig. 6. Hidden terminals for $k = 2$ (above) and $k = 3$ (below) in directional transmission.

2. **Directional transmission**: As above, the probability that a hidden terminal transmits a beacon in the ith slot is $(1-x)^{i-1}x$. Let us denote this probability by $P^{(i)}$. Unlike the omnidirectional case, however, the hidden terminals do not have to start simultaneously to interfere with the reference transmission. As long as the new interferer is on the opposite side to the transmission direction of an existing interferer, the interference can be superimposed (*e.g.*, see Fig. 6). The probability that a hidden terminal transmits a beacon at some point during the vulnerable period of the reference vehicle, whose length is $2b-1$ (Fig. 5) is $P_v = \sum_{i=1}^{2b-1} P^{(i)}$. Thus, the probability that l out of $N/2$ hidden terminals are *scheduled* to transmit a beacon during the vulnerable period is

$$P_{v\mathrm{HD}}[l] = \binom{\frac{N}{2}}{l} P_v^l (1-P_v)^{N/2-l}. \quad (2)$$

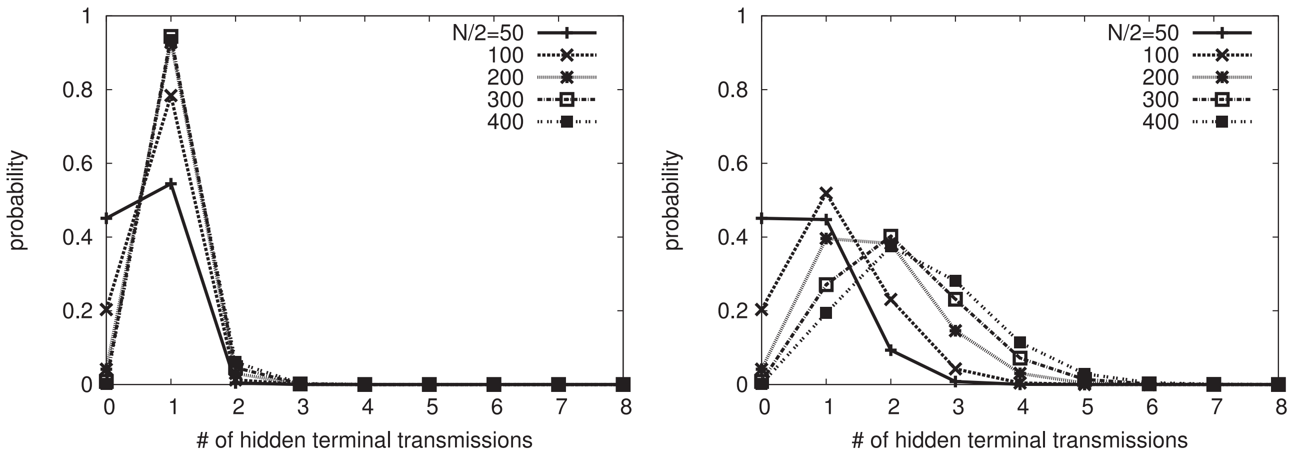
However, note that l scheduled transmissions may lead to fewer *actual* transmissions from the hidden terminals, depending on the time ordering of those terminals' transmission schedules. For example, see Fig. 4(b). Let us index the above scheduled hidden terminals in order of closeness to the reference transmitter. In the extreme case, if the hidden terminal l transmits first, all others to the right of l that sense l's transmission defer their transmission. Thus, only one vehicle, l, works as the hidden terminal. Therefore, given l hidden terminals with their transmissions scheduled within the vulnerable period, we need to compute the conditional probability that k terminals end up actually transmitting, where $1 \leq k \leq l$. For $k = 1$, we have the extreme scenario where node l transmits first. This holds for whatever ordering we have for the scheduled transmissions at all other nodes, and the probability is given by

$$P_a[1|l] = \frac{(l-1)!}{l!} = 1/l,$$

where $l!$ is the number of permutations of the scheduled transmission times of the l vehicles, and $(l-1)!$ is the number of permutations for vehicles other than l.

For $k = 2$, there should be a node $i_1 < l$ that transmits first, which is followed some time later[2] by l (see Fig. 6). For example, if vehicle i_1 transmits directionally, vehicles i_1+1 to l can still transmit, whereas vehicles to i_1-1 must freeze. If l transmits while the reference transmitter is still transmitting, two hidden terminals interfere with the reference node.

[2] Note here that two hidden terminals can transmit *simultaneously*, having used the same contention backoff value. However, in this paper, we classify this case as a collision (at a common receiver), rather than as the hidden terminal problem. We later show that, compared with the hidden terminal problem, collisions are a relatively minor problem in directional communication.



(a) Omnidirectional (b) Directional

Fig. 7. Comparison of concurrent hidden terminal transmissions during the vulnerable period.

There could be zero or more terminals to the right of i_1 that are scheduled between the transmissions of i_1 and l. Let these scheduled transmissions that are suppressed be denoted by j_1. Then, the probability of two actual interfering transmissions from the l hidden terminals is

$$P_a[2|l] = \frac{1}{l!}\sum_{i_1=1}^{l-1}\sum_{j_1=0}^{i_1-1}\binom{i_1-1}{j_1} j_1!(l-j_1-2)!$$

Note that j_1 is not necessarily equal to $i_1 - 1$. Among the $i_1 - 1$ nodes that are silenced by i_1, only some (*i.e.*, j_1) can have beacons scheduled before l, only to be deferred. The others must have been scheduled after l.

Likewise, for $k = 3$, we have two vehicles that transmit before l, denoted by i_1 and i_2, where $i_1 < i_2 < l$. Again, i_1 transmits before i_2. The probability that exactly 3 (out of l) vehicles will interfere with the transmitter is

$$P_a[3|l] = \frac{1}{l!}\sum_{i_1=1}^{l-1}\sum_{j_1=0}^{i_1-1}\binom{i_1-1}{j_1} j_1! \cdot \sum_{i_2=i_1+1}^{l-1}\sum_{j_2=0}^{i_2-j_1-2}\binom{i_2-i_1-2}{j_2} j_2! \cdot (l-j_1-j_2-3)!$$

Again, j_1 is the number of vehicles whose beacons are scheduled between vehicles i_1 and i_2 and located between i_1 and i_2. In the same way, j_2 is the number of vehicles located between i_2 and l that are scheduled after vehicle i_1 but before l.

Generalizing, the probability that, among l scheduled hidden terminal transmissions, there are k actual transmissions is

$$P_a[k|l] = \frac{1}{l!}\sum_{i_1=1}^{l-1}\sum_{j_1=0}^{i_1-1}\binom{i_1-1}{j_1} j_1! \cdot \sum_{i_2=i_1+1}^{l-1}\sum_{j_2=0}^{i_2-j_1-2}\binom{i_2-i_1-2}{j_2} j_2! \cdots \sum_{i_{k-1}=i_{k-2}+1}^{l-1}\sum_{j_{k-1}=0}^{i_{k-1}-\sum_{k=1}^{k-2} j_k-(k-1)}\binom{i_{k-1}-\sum_{k=1}^{k-2} j_k-(k-1)}{j_{k-1}} j_{k-1}! \cdot (l-\sum_{k=1}^{k-1} j_k - k)! \quad (3)$$

Using Eqs. (2) and (3), the probability of k hidden terminals actually transmitting during the vulnerable period around a reference vehicle transmission can be computed as

$$P_{\text{HD}}[k] = \sum_{l=1}^{\frac{N}{2}} P_{\text{VHD}}[l]\cdot P_a[k|l] = \sum_{l=1}^{\frac{N}{2}}\binom{\frac{N}{2}}{l} P_v^l(1-P_v)^{\frac{N}{2}-l}P_a[k|l]. \quad (4)$$

Based on Eqs. (1) and (4), Fig. 7 compares the probabilities of having k overlapping hidden terminal transmissions that affect the reception at the worst positions in the omnidirectional and directional cases. Varying the number of potential hidden terminal vehicles $N/2$ from 50 to 400, we note in Fig. 7(a) that, for omnidirectional communication, the probabilities that either zero or more than one hidden terminals concurrently transmit approach zero as the vehicular traffic density increases. Therefore, in most circumstances, there will be a single hidden terminal interfering with an ongoing reception. However, for directional communication, the probability of more than one hidden terminal interfering with a given reception steadily increases with vehicle density. The presence of a single interferer may not necessarily corrupt the given reception, because the capture effect may help the receiver to decode either message. However, as multiple interferers come within the hidden terminal range, even that becomes less probable, because the reception is more likely to be affected by the cumulative interference power. This difference in the number of concurrent interferers shows that using directional transmission alone can potentially worsen the packet reception, although the channel utilization is reduced, as we saw in Fig. 3.

In summary, the above exercise indicates that we must introduce a counter-measure to reduce the number of *concurrent* hidden terminal transmissions in order to take advantage of the reduced channel utilization attained by directional messaging. In the next section, we propose a novel approach based on the findings of above analysis that utilizes the geographical information carried in the safety messages themselves.

3. Geographical scheduling

The analysis of Fig. 6 in the previous section yields an insight into how the problem could be eliminated: *the ordering of the transmissions should follow their directionality*. In other words, the temporal ordering of the transmissions should be aligned with the spatial ordering. In Fig. 4, for instance, l should transmit first, followed by

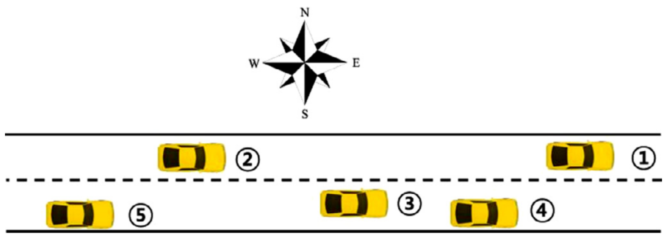


Fig. 8. Example of bad ordering: vehicles are moving eastward, and transmitting toward the rear.

$l-1, l-2, \ldots$. In this way, we can reduce the number of hidden terminals that cumulatively affect the reference transmitter and its receivers to one. Moreover, we can maximize the distance between the reference transmitter and the hidden terminals. Owing to the capture effect working for the reference transmitter, this should minimize the impact of distant hidden terminals on the intended receivers of the reference transmitter.

3.1. Spatial structure for scheduling

To ensure that spatial ordering dictates the message transmission scheduling, we utilize the vehicle position information already embedded in beacons such as BSMs [4] or Cooperative Awareness Messages (CAMs) [16]. We refer to this as *geographical scheduling*. In the WAVE environment, vehicle position information is available as Global Positioning System (GPS) coordinates, but simply taking either the latitude or longitude as the ordering criterion is an inappropriate method of ordering vehicles in the message transmission direction. To take an extreme example, if we used the latitude, the intended spatial ordering would most probably fail for vehicles running on roads that run precisely eastbound, as illustrated in Fig. 8. In the example, the proper transmission order for minimizing the hidden terminal problem should be $1 \to 4 \to 3 \to 2 \to 5$, but latitudinal ordering will give $1 \to 2 \to 3 \to 4 \to 5$.

What should be observed above is that the *heading* of the vehicle flow is critical in the positional ordering of the vehicles. That is, the GPS coordinates of the vehicles should be ordered with respect to the heading of the vehicle flow, before they are compared. To use the vehicle heading information for scheduling, we exploit the heading information in the beacon message. For instance, the "Heading" field in the Society of Automotive Engineers (SAE) J2735 BSM is a 2-byte field that specifies the direction of vehicle movement in units of 0.0125°, so that 28,799 such degrees represent 359.9875° from north [4]. Commercial vendors make this information available in the beacon messages transmitted from their on-board units (OBUs) [17].

By exchanging beacon messages, each vehicle can determine its transmission order relative to its neighbors. Note that the heading values of vehicles running in generally the same direction can differ on a microscopic scale. Moreover, on a winding road, the heading values can vary wildly among a group of vehicles running in close proximity. For instance, a ring road and a sharp turn will definitely yield rapidly changing headings. However, between consecutive vehicles, the heading difference should not be close to 180°, which would generally indicate a beacon from a vehicle on the opposite side of the road. In this paper, we use a threshold value of ±90° in the heading difference to distinguish the direction.

The final building block for the spatial ordering of the vehicles is the translation of their measured position value as the heading value is rotated onto the longitude, *i.e.*, the north axis. Fig. 9 illustrates this operation. If θ_i is the (acute) angle between the heading of vehicle V_i and the longitude and (x_i, y_i) is the GPS measured position, the translated position (x_i', y_i') after rotation is given by

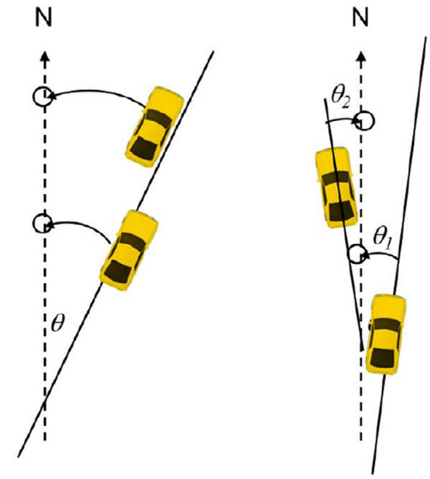


Fig. 9. Mapping the heading to north by rotation.

$$\begin{bmatrix} x_i' \\ y_i' \end{bmatrix} = \begin{bmatrix} \cos(-\theta_i) & -\sin(-\theta_i) \\ \sin(-\theta_i) & \cos(-\theta_i) \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix}$$

Note that the rotation operation works for heading values on either side of the longitude (Fig. 9, right). After rotation, the vehicle positions are sorted to fix the transmission order given in the temporal structure discussed below.

3.2. Temporal structure for scheduling

To ensure that the beacon transmitting application can directly control the transmission schedule, we use the notion of abstract application-level reference timing slots called "epochs," as proposed in our previous work [18,19] and some other papers under a different nomenclature [20]. The time axis is regarded by the messaging application as being divided into epochs of equal duration, just long enough to accommodate a single beacon message transmission, *e.g.*, 500 μs. The epochs repeat every I ms, *e.g.*, $I = 100$ in the default IEEE 802.11p Sync Interval (SI), whereas the CACC application requires 25 Hz [8], meaning $I = 40$. Without any initial information, each vehicle first selects a random epoch within an interval. Through the exchange of beacons, however, the vehicles eventually determine the proper epoch in which to transmit their beacons according to their spatial order, as calculated in the previous section. If the beacon transmission order disagrees with the order of vehicle positions in the Heading direction, it should be modified in the next period.

Because we use slack epochs for beacon transmission, the channel is typically idle after the beacon transmission for more than the 802.11 Distributed Coordination Function (DCF) Interframe Space (DIFS). In the IEEE 802.11 MAC, if the channel is idle for longer than one DIFS, packets can be transmitted without the usual backoff operation. This post-backoff (or direct access) feature of the 802.11 MAC protocol would make transmissions using the same epoch certain to collide. To avoid deterministic collisions, each application is allowed to add a small random time offset (jitter) to the transmission start time [19] (Fig. 10).

3.3. Scheduling algorithm

Based on the spatial and temporal structures defined above, we now design a geographical scheduling algorithm.

When a vehicle V_h receives a beacon from another vehicle V_i in epoch e_k, it executes the *RECV* function shown in Algorithm 1. V_h first determines whether to heed the message by checking that the distance between the vehicles is within *SafetyDistance*, which is set to

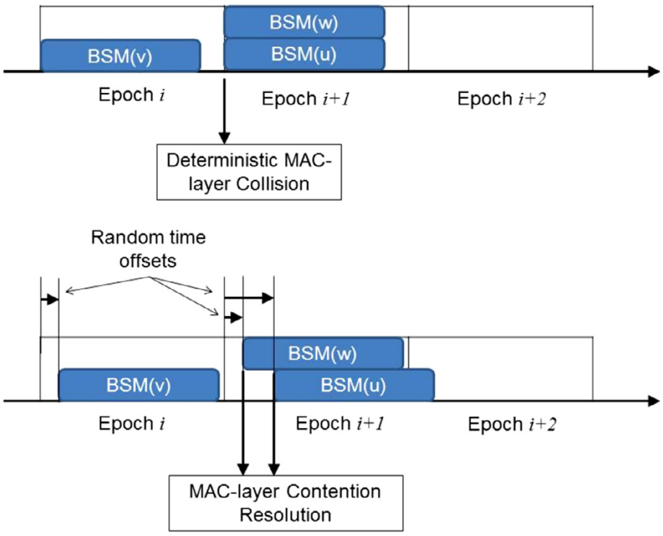


Fig. 10. Post-backoff transmission (above) and application-jittered transmission (below) in epochs.

Algorithm 1 *RECV*(V_i, *Pkt*, e_k): Vehicle V_h receives beacon from V_i in epoch e_k.

1: $\{\{V_n\}$: Neighbors table$\}$
2:
3: **if** $Distance(V_h, V_i) \le SafetyDistance$ **then**
4:     **if** $V_i \notin \{V_n\}$ **then**
5:         $\{V_n\} \leftarrow V_i$ ▷ Insert V_i into $\{V_n\}$
6:     **else**
7:         Update V_i's information in $\{V_n\}$
8:     **end if**
9:
10:     $posOrder = getPositionOrder(V_h, V_i)$
11:
12:     **if** $posOrder \neq -1$ **then**
13:         $e(V_h) \leftarrow e_k + posOrder$
14:         ▷ Schedule next beacon in epoch $e_k + posOrder$
15:
16:     **end if**
17: **end if**

---

300 m in this paper (line 3). If so, V_h updates its neighbors table $\{V_n\}$ with the information from V_i. Next, V_h ascertains its transmission order in the direction of its movement by calling the *GetPositionOrder* function (Algorithm 2). Note that beacons from vehicles behind V_h cannot be heard by V_h, because they are only transmitting in their upstream direction. If V_i is moving in a direction of no interest to V_h (*e.g.*, running on the opposite side of the road), the *GetPositionOrder* function returns a negative result, and the beacon is not used for ordering. Otherwise, the computed value *posOrder* (line 10) gives the number of vehicles between V_i and V_h. This value is added to the current epoch e_k to yield V_h's epoch. In this way, epochs are sequentially assigned to vehicles moving in the same direction so that their transmissions do not overlap in time and space.

Algorithm 2 describes the *GetPositionOrder* function, which computes the number of vehicles between the beacon transmitter V_i and the receiver V_h. First, V_h compares its heading with that of V_i. If they are generally in opposite directions, the function returns a negative result. The parameter δ determines how the opposite direction is defined; as mentioned above, we have set $\delta = 90°$. The position of V_i is then rotated onto the reference axis (*i.e.*, north), and compared with the geographical positions of neighbors V_n and V_h. In this sorted order, the position offset of V_h from V_i is computed and returned in terms of the number of vehicles between them.

Algorithm 2 *GetPositionOrder*(V_h, V_i).

$\{x_k, y_k = V_k$ longitude, latitude$\}$
$\{\theta_k = V_k$ heading value (degrees)$\}$
$\{\{V_n\}$: neighbors table$\}$

if $180° - \delta \le |\theta_i - \theta_h| \le 180° + \delta$ **then**
    return -1
    ▷ V_i is headed in the opposite direction to V_j
else

$$pos(V_i) = \begin{bmatrix} cos(-\theta_i) & -sin(-\theta_i) \\ sin(-\theta_i) & cos(-\theta_i) \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix}$$

    ▷ Rotate V_i coordinate onto North
    Sort $pos(\{V_n\})$
    Return the offset of V_h from V_i in the sorted order
end if

Before transmitting a beacon, each vehicle determines its position among its neighbors using the neighbor table. For this purpose, all neighbor vehicle positions are extrapolated from the last reported positions in their received beacons. This neighbor position estimation is common to most V2V applications running on commercial OBUs. Even if no beacons arrive from a forward vehicle, its position is extrapolated based on its last beacon up to a certain time threshold. In our experiment, the threshold is set to 3 s. That is, the extrapolation is terminated if a beacon does not arrive from a forward vehicle for 3 consecutive seconds, and the vehicle is determined to have disappeared. At 25 Hz, this amounts to 75 consecutive beacon losses. This conservative behavior is intended to ensure that the algorithm does not easily mistake a lack of beacons from forward vehicles for the disappearance of these vehicles. For example, even if the beacon loss probability is as high as $p = 0.9$ (which would only happen when the receiver is far away, *e.g.*, 400 m in Fig. 12), the probability of 75 consecutive losses occurring is $p^{75} \approx 3.7 \times 10^{-4}$, which is practically zero. This probability is likely to be even smaller in close proximity. Under the extremely small probability that 75 consecutive losses should happen, the vehicles behind the unfortunate vehicle will advance by one epoch, which may cause signal collisions. However, the random jitter at the beginning of the epoch (Fig. 10) will eventually resolve this issue. The epoch assignment in the following vehicles will then revert to the previous one.

The algorithm complexity is relatively low, and can be quickly executed on most embedded devices. For example, we measure that Raspberry Pi 2 model with 900 MHz clock and four cores can compute the position ordering by Algorithm 1 on 22,900 beacons per second. Since vehicles beaconing at 10 Hz in bumper-to-bumper situation on a four-lane road over 300 m communication range will collectively generate only 2400 beacons, the position ordering algorithm execution algorithm is unlikely to be a bottleneck.

Fig. 11 shows the epoch assignment behavior (a) at the start, (b) with the addition of new vehicles, and (c) with the removal of vehicles. Here, vehicles use 25 Hz beaconing, so the period is 40 ms. The period axis represents the flow of time, where the vertical axis is the chosen epoch number. We assume that there are 80 epochs in each period. In the figure, (a) shows the epoch selection dynamics at the start of the simulation. Here, the inter-vehicle distance is set to 10 m. We can see that vehicles randomly choose epochs at period 0, but within 5 periods, the epochs of the vehicles are completely aligned to their respective positions. We then double the number of vehicles at around period 50, as manifested by the irregular spikes in (b). This sudden increase in the vehicle population can occur around an intersection or a merging road that injects vehicles into the given traffic flow. In this case, the epochs used by the vehicles are

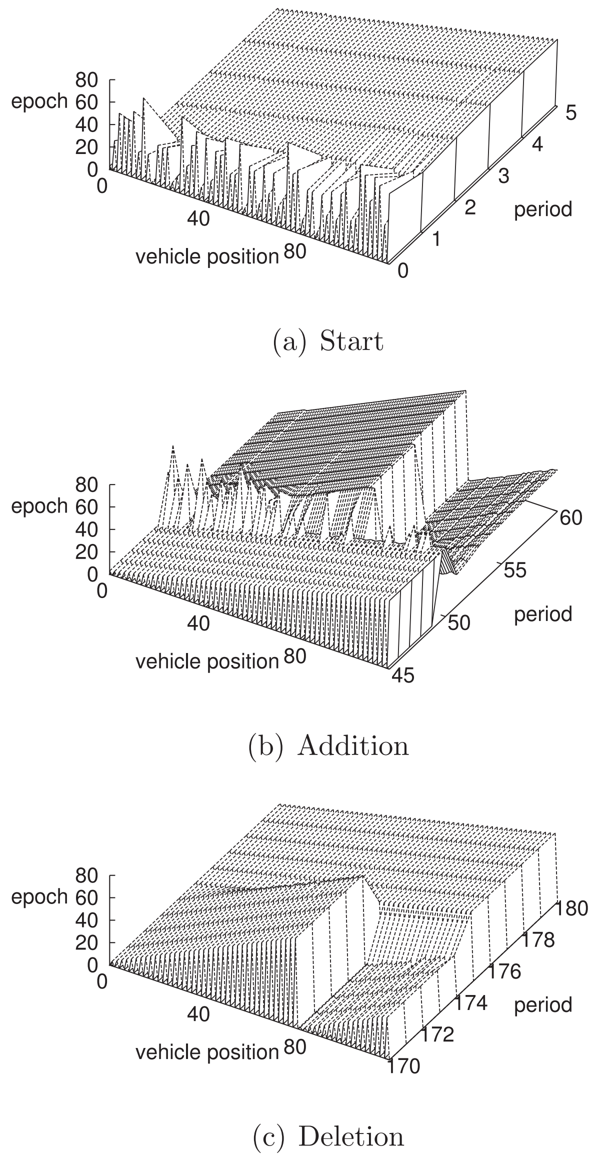


Fig. 11. Epoch alignment dynamics of Algorithm 1.

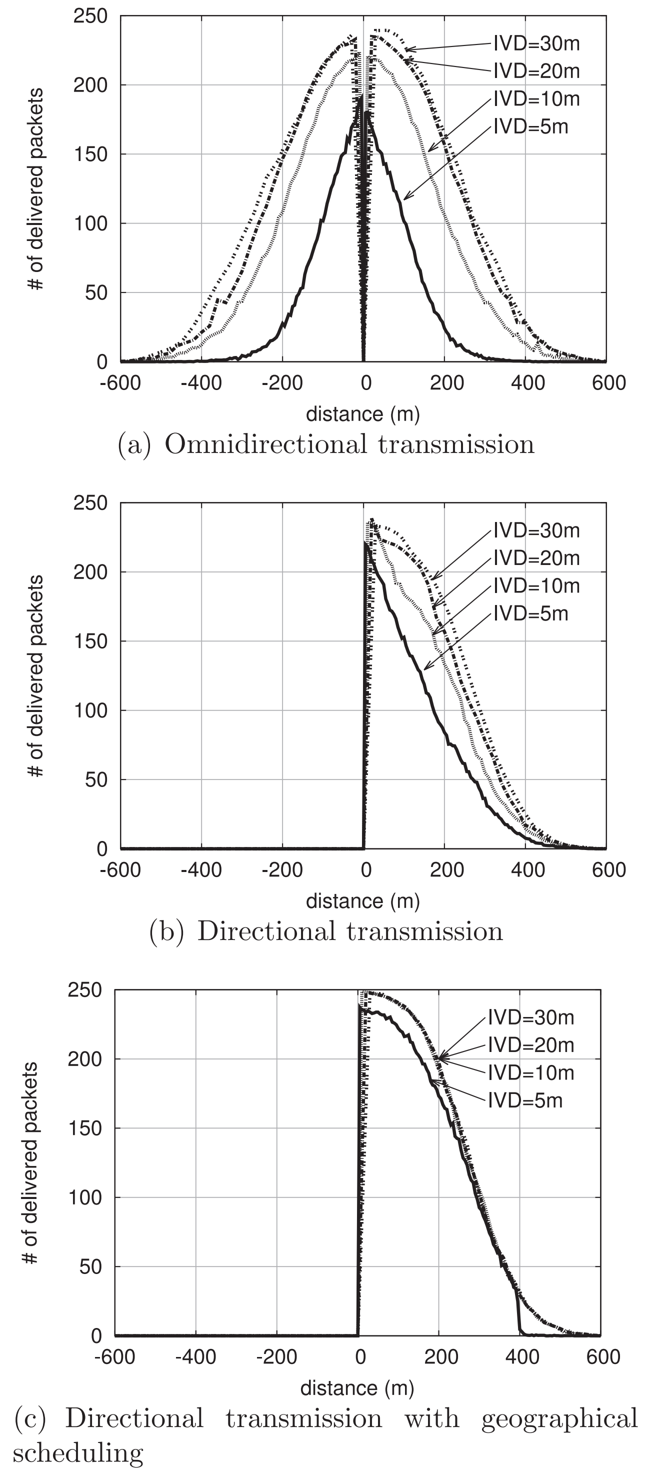


Fig. 12. Performance comparison of three schemes: omnidirectional, directional, and directional transmission with geographical scheduling.

effectively rearranged within 10 periods. Starting from vehicle 81, we can see that epochs are reused, as there are only 80 epochs in a period. In this case, the inter-vehicle distance is 5 m, so it is the most congested situation. Despite some message collisions, the epoch selection algorithm quickly realigns the epochs to be used by vehicles. As the epoch selection depends on the neighboring vehicles, losses due to poor channel conditions are less of a problem, because the beacon communication with neighbors takes place over a short distance. In (c), we remove half the vehicles, which models the situation where many of the vehicles in the current traffic flow leave at a busy exit. Again, the proposed algorithm quickly determines a new alignment.

3.4. Performance evaluation

In this section, we evaluate the performance of the proposed scheme. Although there are numerous proposals for directional communication in the contexts of ad hoc networking, sensor networking, and vehicular communication, most deal with unicast communication (*e.g.*, [21,22]). Studies that have considered broadcasts with directional transmission tend to focus on multi-hop relaying or propagation (*e.g.*, [23,24]). To the best of our knowledge, the current study is the first to deal with one-hop broadcast using directional communication. Because of the paucity of directly comparable proposals, we choose to compare the following three schemes.

1. IEEE WAVE with omnidirectional communication alone;
2. IEEE WAVE with directional transmission and omnidirectional reception, but without geographical scheduling;
3. IEEE WAVE with directional transmission, omnidirectional reception, and geographical scheduling.

Below, we examine the performance of these schemes in two scenarios: single direction vehicle flow and bidirectional traffic flows.

3.4.1. Single direction traffic flow

Now, Fig. 12 compares the delivery performance of the three compared schemes. The most notable facet of this result is that the geographical scheduling outperforms the other two schemes in all traffic densities. Moreover, the number of successful beacons is almost identical, irrespective of the IVD. One noticeable deviation from this general trend is the result for IVD = 5 m at more than 400 m from the reference vehicle, where it bottoms out slightly earlier than in other densities. This is because of the epoch reuse and power capture. With IVD = 5 m, there are 80 vehicles in the 400 m range where the sudden drop is observed. This is equal to the number of epochs in a period of 40 ms, which is given by the 25 Hz requirement. Thus, beyond 400 m, the transmission from the reference vehicle overlaps with that from another vehicle, say V_k, that is using the same epoch. Hence, the reference vehicle is a hidden terminal for V_k, but owing to the power difference, the receivers beyond V_k capture only V_k's transmission. Still, even this result is not worse than the omnidirectional result with the same traffic density of IVD = 5 m (see Fig. 3). Moreover, 400 m is well above the typical safety distance for most V2V crash avoidance applications.

Fig. 13 shows the breakdown of the beacon losses in the three compared schemes under the most heavy vehicular traffic scenario with IVD = 5 m. The horizontal axis shows the distance from the beacon transmitter, and the vertical axis gives the number of lost beacons out of 250 transmissions for each position. The total losses include those due to the hidden terminal problem, collisions, deafness (directional only), and channel-induced losses. The channel losses due to path loss and fading can be implicitly estimated by subtracting the previous three factors from the total loss. The hidden terminal losses are a conservative estimate, as we classify overlapped packet transmissions with starting times of less than an 802.11p contention slot size ($\sigma = 13\,\mu s$) apart as a collision. In Fig. 13(a), we note that collisions are a major source of the losses in omnidirectional transmission, more so than the hidden terminal losses for most distances. This is a consequence of the unnecessary spillover of beacons in unwanted directions. Fig. 13(b) shows that directional transmission significantly reduces the number of collisions by eliminating the spillover. However, the hidden terminal problem is indeed exacerbated, especially for shorter, more safety-critical distances [25], as these are more heavily affected in directional communication (see Fig. 4). The aggravated hidden terminal problem undermines the gain from the collision reduction. Still, the total number of lost packets under directional transmission is visibly lower than with omnidirectional transmission, although this is the only clear winning case for the vanilla directional communication scheme, as we saw in Fig. 3. Enhancing this approach with geographical scheduling, however, significantly reduces both the number of collisions and the hidden terminal losses (Fig. 13(c)), especially for shorter distances. Even at close proximity to the transmitter, the original omnidirectional transmission has a success rate of only just over 70%. In contrast, the proposed scheme achieves over 90% delivery. At 100 m, omnidirectional messaging has only a 40% successful delivery rate, whereas the proposed scheme achieves 90%. At 200 m, the success rate with the omnidirectional method is approximately 10%, whereas it is approximately 75% with the proposed scheme. At 300 m, omnidirectional transmission rarely succeeds, but directional transmission with geographical scheduling still enjoys a 40% success rate. The proposed scheme outperforms omnidirectional transmission over the entire range of distances, with a minor exception at around 400 m, although in this case the latter also has a negligible success rate. As shown in Fig. 12, the receiver at 400 m that is using the same epoch as the reference transmitter is effectively deaf. Given the contention window size of $CW_{min} = 3$, the deafness has a probability of 10/16. This is because there are 10 out of 16 cases where the contention backoff value chosen by the receiver is less than or equal to that of the reference transmitter. With 250 messages, this leads to over 150 deafness losses, as borne out by the simulation. Finally, collisions are also largely avoided because vehicles are eventually assigned a separate epoch in which to transmit their beacons. Consequently, in the single direction traffic flow scenario, path loss and fading are the dominant sources of failed deliveries for geographical scheduling.

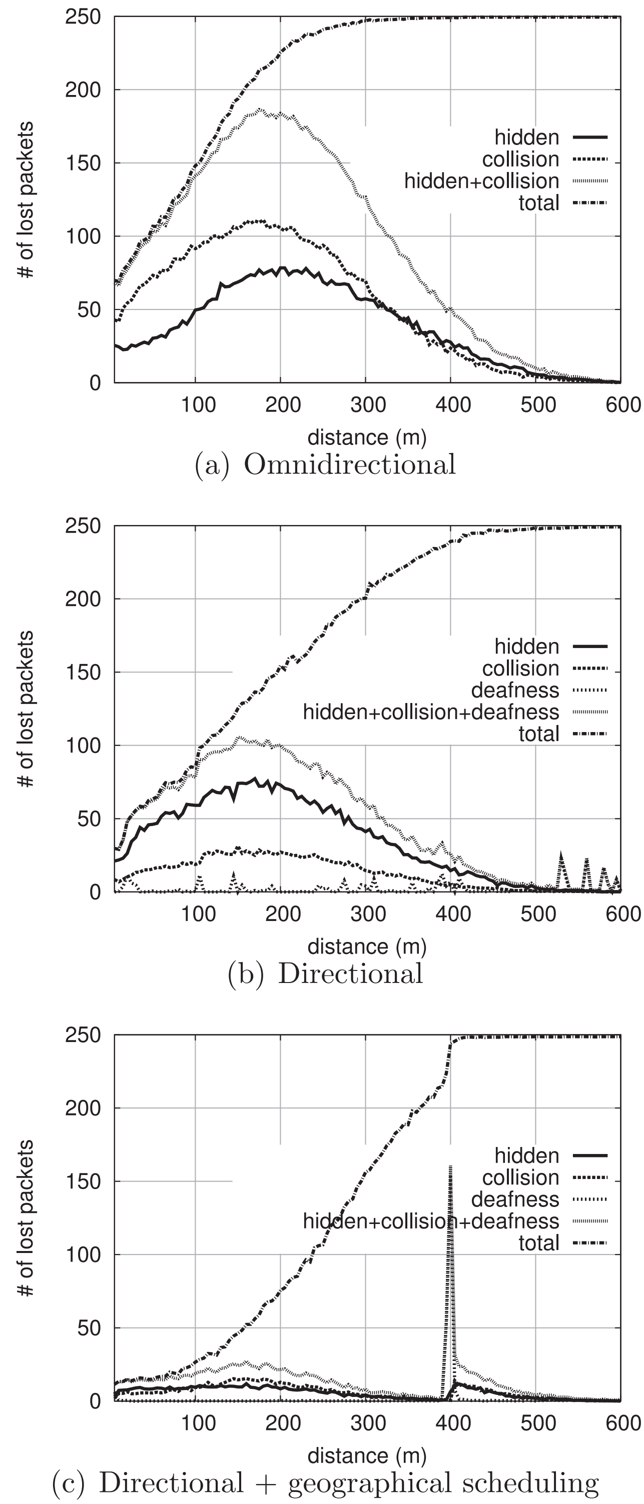


Fig. 13. Loss breakdown, 250 beacon transmissions, IVD = 5 m.

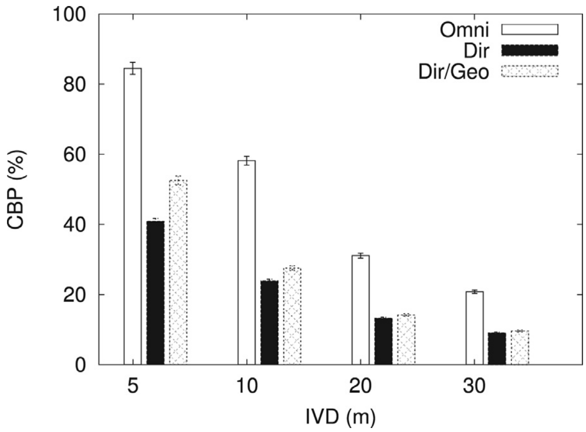


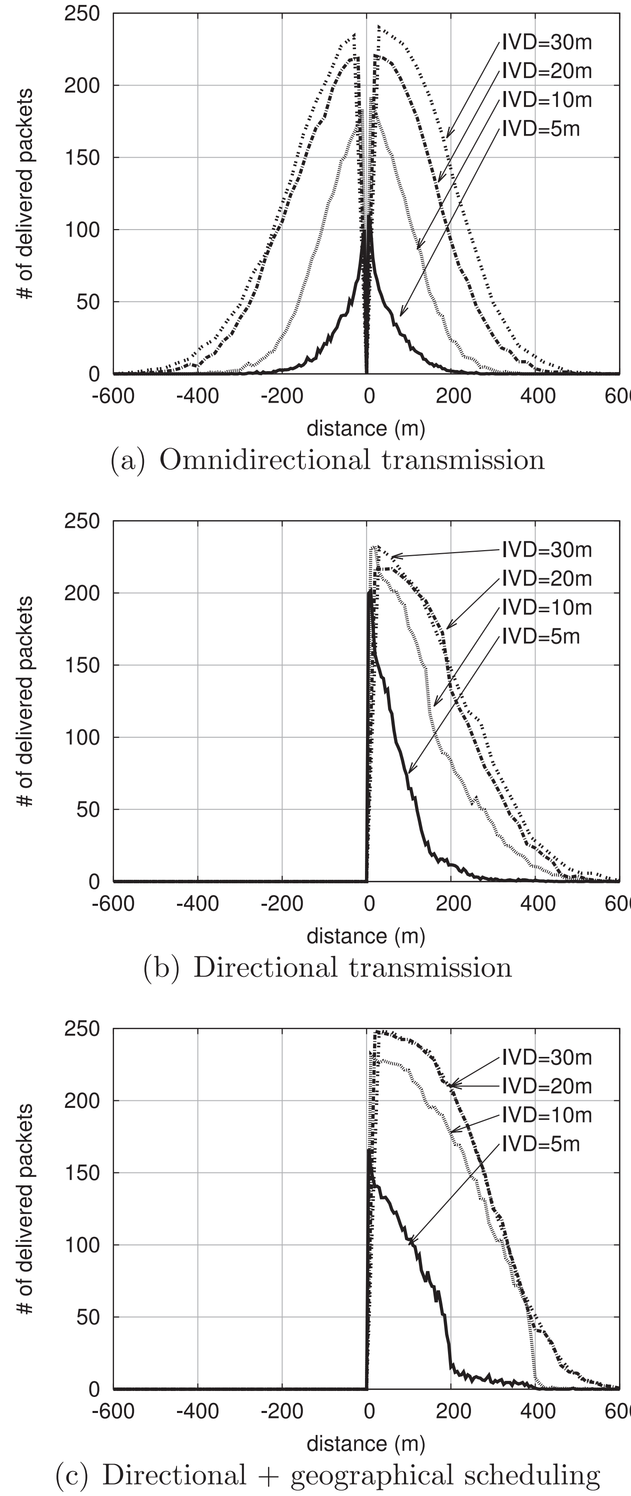
Fig. 14. Average channel busy percentage (CBP), with 95% confidence interval.

Fig. 14 shows the average channel busy percentage (CBP) for the three schemes, with 95% confidence intervals. First, note that the use of directional communication reduces the channel load by 50% for all tested vehicle traffic densities. Although the load reduction does not entirely translate to an increased delivery rate, directional transmission indeed frees the channel of some unnecessary traffic. We can also observe that, when geographic scheduling is combined with directional transmission, there is less reduction in channel load. This is explained by the reduction in the number of collisions (see Fig. 13(c)). When collisions occur, the channel busy percentage decreases, because the channel is simultaneously used (but this is obviously unproductive). In contrast, if collisions are resolved, the non-overlapping packets take up more time resources. Still, geographic scheduling saves more channel time than omnidirectional communication. Thus, the use of geographical scheduling is indeed effective in reaping the benefits of directional transmission, as it drastically reduces both collisions and hidden terminal losses.

3.4.2. Bidirectional traffic flows

We now consider a more realistic setting in which traffic is flowing in opposite directions. By adding traffic on the opposite side of the road, the vehicular traffic density is doubled, but the vehicle traffic density measure (*i.e.*, IVD) will still be given with respect to a single direction, for ease of comparison. For the geographical scheduling scheme, we assume that vehicles use time division multiplexing of epochs between opposite direction flows [26]. That is, one side of the road uses odd epochs, whereas the other side uses even epochs. As to how to enable vehicles to determine which epochs are available to them, external assistance is desirable. For this purpose, the J2735 Traveler Information Message (TIM) could be leveraged. The TIM specifies the heading values to which the message applies in the data frame header [4]. Hence, for one direction, the RSU would issue the TIM Forward Travel to vehicles with the corresponding headings so that they use one set of epochs, and for the other direction, the RSU would issue Reverse Travel so that they use the other set [4].

A non-RSU-assisted alternative could be what VeMAC proposes [27]. In VeMAC, lane directions are classified by the GPS-based vehicle heading into “left” (which includes south) and “right” (which includes north). Our scheme performs similar computation when filtering incoming beacons, so the VeMAC lane classification method can be easily incorporated into our scheme. Since the GPS-based heading information should be readily available on the WAVE OBU, and the scheme works in the absence of RSUs, it would be more practicable than using J2735 TIM message broadcasts by RSUs. In the following discussion, we assume that this partitioning has been conducted so that opposite traffic flows use alternate epochs.



(a) Omnidirectional transmission

(b) Directional transmission

(c) Directional + geographical scheduling

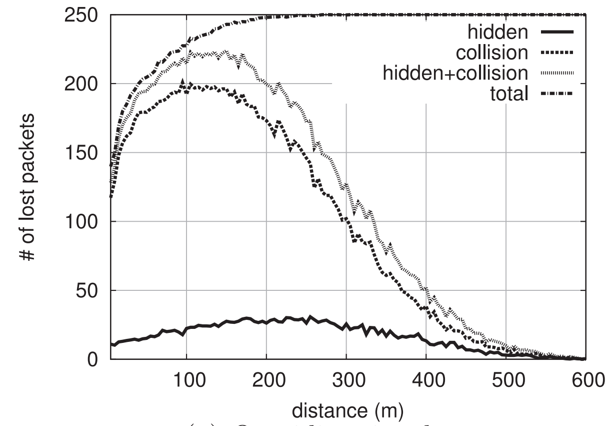
Fig. 15. Packet delivery with and without directional communication (opposite traffic flows).

Fig. 15 shows the number of successfully delivered packets for the three compared schemes. As a consequence of the doubled vehicle population, we observe that the delivery rates of all three schemes are degraded to varying degrees. For instance, under omnidirectional communication, the maximum number of delivered packets with IVD = 5 m is 100, down from 150 in the single-direction scenario. However, for the very sparse scenarios, *e.g.*, IVD = 30 m, the channel can still accommodate the heavier volume of traffic, so the delivery rate remains approximately the same. The directional scheme without geographical scheduling shows a similar visible degradation, except for IVD = 30 m. Again, this scheme is slightly worse than the omnidirectional scheme at IVD = 30 m when close to the reference transmitter.

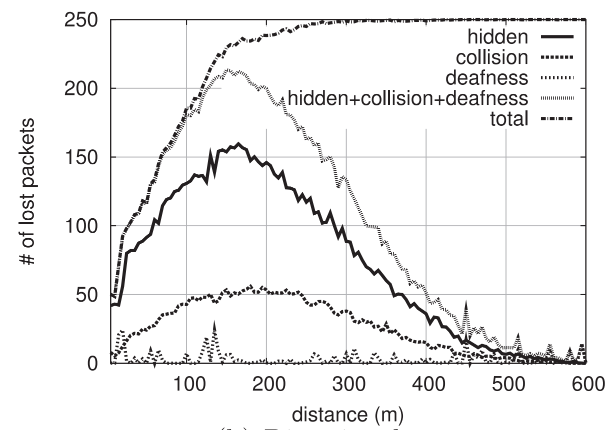
With geographical scheduling, the highest traffic density scenario (IVD = 5 m) suffers from lower delivery rates, whereas at lower densities its performance is almost the same as in the single-direction flow scenario. Still, it significantly outperforms the two comparative schemes. According to the requirements established by the Dutch Connect and Drive (C&D) project [15], the CACC application should generate beacons at 25 Hz, and the reception should not go below 10 Hz (*i.e.*, 40% delivery rate). Additionally, the CACC traffic information should reach at least 200 m or 15 vehicles per lane in the upstream direction. From Fig. 15, for the problematic case of the heaviest congestion (IVD = 5 m), all three schemes fail to meet the 40% requirement at 200 m. However, both geographical scheduling schemes meet the alternative 15 vehicle (or equivalently at 30 m distance with IVD = 5 m) requirement. In contrast, the omnidirectional scheme does not meet this alternative requirement. For IVD = 10, 20, and 30 m, the geographical scheduling scheme exceeds 40% delivery at the specified 200 m distance. However, the two comparative schemes only meet this requirement at one or two lower-density cases. The omnidirectional scheme barely reaches a 40% delivery rate for IVD = 30 m, and the vanilla directional scheme meets the requirement for IVD = 20 and 30 m. This example certainly illustrates the utility of the proposed scheme.

Fig. 16 shows the breakdown of the losses for IVD = 5 m, the worst-case congestion. (In all lower traffic-density cases, geographical scheduling is the clear winner, as shown in Fig. 15.) Due to the doubled channel load, we can see that collisions increased significantly for the omnidirectional scheme (a). Indeed, there are so many losses classified as collisions that the hidden terminal losses appear reduced compared to the single-direction traffic flow scenario in Fig. 13. For the directional schemes (b) and (c), both collisions and hidden terminal losses are amplified compared with the single-direction traffic flow scenario. For geographical scheduling, the collision losses are comparable to the directional transmission case up to 200 m, but the hidden terminal losses are lower. We can see that the difference between the two directional transmission schemes in terms of the total loss up to a distance of 200 m is due to the reduction in these hidden terminal losses. Up to 200 m, geographical scheduling generally yields lower total losses than the other schemes. Again, the surge of hidden terminal losses at 200 m and the deafness losses at multiples of 200 m both stem from the reuse of epochs. In particular, the three vehicles receiving the reference vehicle's beacon each lose approximately 50 due to deafness, sharing the 150+ losses seen in the single-direction flow case in Fig. 13(c).

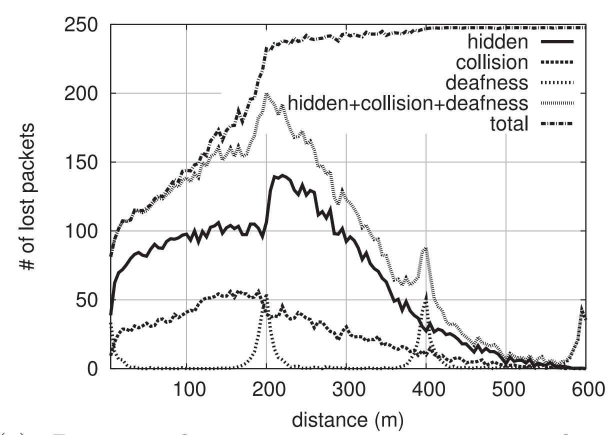
Finally, Fig. 17 shows the average CBP in the bidirectional vehicular traffic scenario. For all three schemes, the CBP is higher than in the single-direction traffic scenario, but both directional transmission schemes exhibit lower channel usage than the omnidirectional scheme.



(a) Omnidirectional



(b) Directional



(c) Directional transmission + geographical scheduling

Fig. 16. Loss breakdown, 250 beacon transmissions, IVD = 5 m (bidirectional vehicle traffic flows).

3.4.3. Mobility

Thus far, to clearly observe the dynamics of the compared algorithms, our experiments have been configured so that the relative vehicle positions do not change. In reality, however, the relative positions of vehicles are constantly disrupted by overtaking, joining, and departures through exits, entrances, and intersections. In this section, we relax the fixed relative position assumption, and compare geographical scheduling with the other schemes under dynamic topology changes due to vehicle mobility.

In safety-critical V2V communications, the beacons are transmitted at a high rate, *e.g.*, 25 Hz (=1 every 40 ms), so vehicle movement within one beacon period is small. For instance, at 100 km/h, a vehicle advances approximately 1.1 m in 40 ms. Moreover, because the vehicles move according to the car following model, the relative speed difference among vehicles moving in the same direction will be much smaller than, say, 100 km/h. Therefore, local vehicle order reversals within 40 ms will be infrequent events. However, suppose vehicles A and B experience such a reversal. That is, in the previous beacon exchanges, the reported order was A → B, but 40 ms later, the topological order of the vehicles has changed to B → A. Note that all the preceding vehicles that lie ahead of A and B are unaffected, because they transmit earlier than these two vehicles. The following vehicles, on the other hand, do not observe any change in their

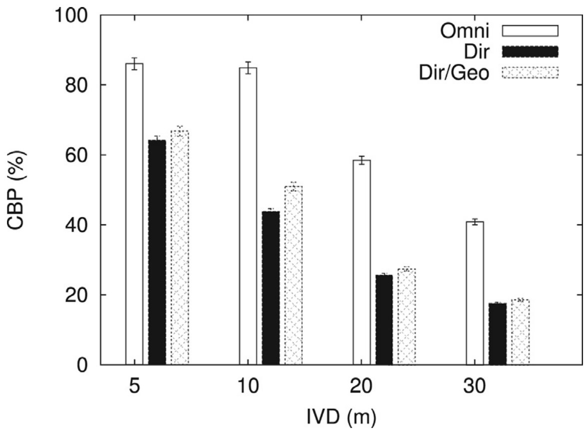


Fig. 17. Average CBP, with 95% confidence interval (opposite traffic).

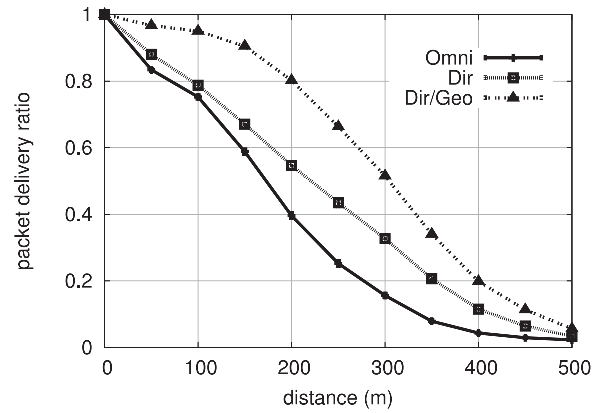


Fig. 18. Packet delivery ratio (PDR) comparison under dynamic mobility.

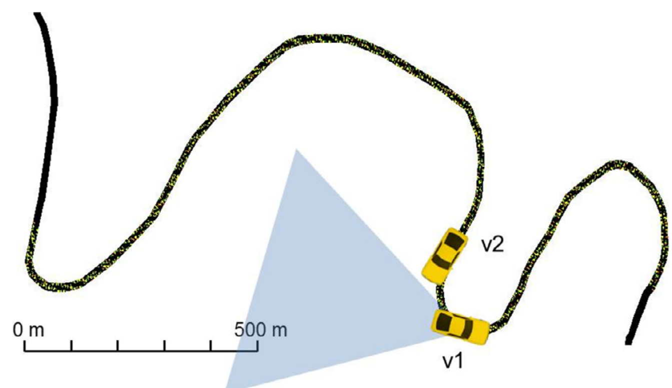


Fig. 19. Layout of a winding road used in the simulation.

own order, because the number of vehicles remains unchanged. The problem reduces to how A and B exchange their epochs to reflect the change in topological order. Vehicle A cannot identify this physical change unless it hears from B, so it transmits earlier than B as before. Now located behind B, A's directional transmission does not reach B. Thus, it is as if B missed the transmission from A in A's expected epoch. Because missing a beacon can be caused by other conditions (*e.g.*, channel loss), B does not move its epoch immediately. However, A suddenly begins to receive B's beacon after its transmission, but the information in the beacon states that B's geographical position is actually ahead of A. Vehicle A now realizes that it should switch epochs with B. Moreover, A knows that, without its help, B cannot identify the reversal, as A is now behind B. Therefore, under our protocol, A transmits omnidirectionally when it identifies a reversal. This enables B to receive A's transmission and switch epochs with A. Because B may miss the omnidirectional transmission from A, this omnidirectional communication is repeated until B starts to transmit earlier than A, *i.e.*, in A's old epoch. Until B hears A's omnidirectional transmission, B will attempt to transmit in its old epoch. However, because both A and B apply a random jitter, B eventually hears A's transmission (*i.e.*, A gets to transmit earlier in the epoch). Vehicle B can then move to A's old epoch.

For an experimental validation, we change some of the simulation configurations in Table 1. We let 500 vehicles run on a three-lane road for 100 simulated seconds. The average traffic density is set to 125 vehicles per km, and the average vehicle speeds on the three lanes are 10, 15, and 20 m/s, respectively. The mobility pattern for the vehicles is generated by SUMO-0.16.0 [28]. In particular, we use the Krauss car-following model provided by the SUMO package. The acceleration, deceleration, and driver imperfection parameters used in the model are 0.8, 4.5, and 0.5, respectively. In the simulation, the number of overtaking or overtaken events for each vehicle is approximately 102.92, which indicates that each vehicle experiences a topology change once a second on average. These higher-than-reality topology dynamics are used to place the geographical scheduling algorithm under maximum stress. The other parameters are the same as in Table 1.

Fig. 18 shows the average packet delivery ratio (PDR) for the beacons transmitted from a reference vehicle for the three comparative schemes. Because the relative positions of the vehicles are constantly moving, we use 50 m bins to collect reception statistics and compute the averages. For instance, the points at 50 m are the average PDRs for the three schemes for vehicle positions from 0 to 50 m (the PDR of 1 at a distance of 0 m in the graph serves only as a reference point). The most notable aspect of the results is that the geographical scheduling scheme still clearly outperforms the other schemes under heavy topology changes. In contrast, the vanilla directional scheme exhibits up to a 20% lower PDR than geographical scheduling enhancement. This is due to the aggravated hidden terminal problem in directional communication. Moreover, omnidirectional communication gives the lowest PDR, a result of the high CBP caused by unnecessary message propagation. The PDR difference reaches 40%. In summary, the packet delivery performance of geographical scheduling that was observed in the static relative topology scenarios is repeated in the dynamic topology situation.

3.4.4. Vehicle flow on a winding road

In this experiment, we placed the proposed algorithm under a different kind of stress, by exposing it to a winding road environment. Here, following vehicles may lose the directional transmission from a vehicle in front when the road turns sharply. For example, in Fig. 19, V_1 is transmitting beacons toward the rear (*i.e.*, in the shaded triangle), but the following vehicle V_2 cannot hear them. The model in the figure is from a 3 km strip of road situated in a mountainous region in Korea, created in our simulation using OpenStreetMap [29]. In this experiment, we set the average inter-vehicle distance to 11.76 m.

Fig. 20 shows the PDR result for 100 simulated seconds. Again, we use the 50 m bins. Note that directional transmission with geographical scheduling exhibits the best performance. At the most critical distance of 100 m, the scheme improves upon omnidirectional communication by 40% and upon vanilla directional communication by 20%. At 200 m, the corresponding improvements are 50% and 30%. We observe that despite occasional losses of the directional messages, the proposed scheme outperforms the two comparative schemes.

The PDR result only tells us about the average performance, which may be dictated by that along the relatively straight parts of the given road strip. Thus, we further check the packet loss pattern through the inter-packet gaps (IPGs) of the three schemes in Fig. 21. If the directional communication schemes lose a batch of beacons through the

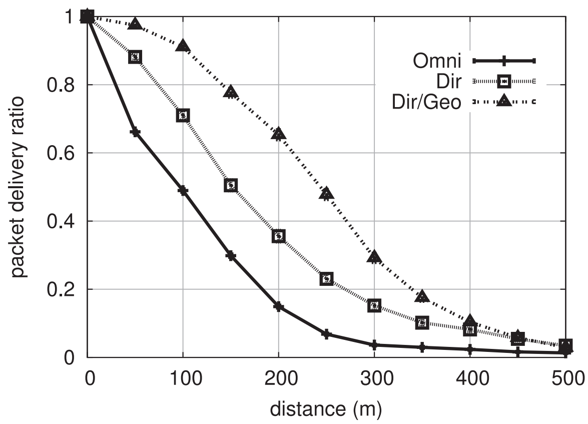


Fig. 20. PDR comparison over the curved road.

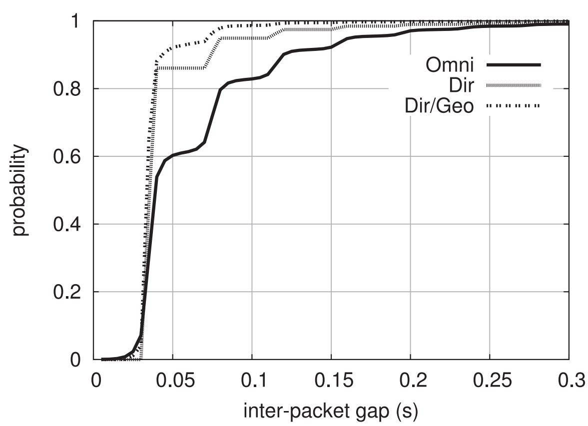


Fig. 21. Inter-packet gap distribution.

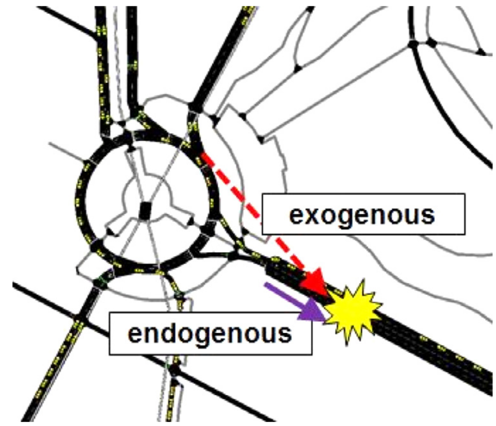


Fig. 22. The SUMO model of Columbus Circle in New York City.

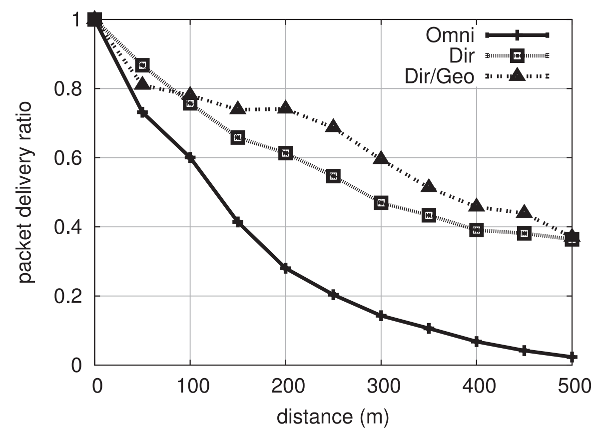


Fig. 23. PDR drop due to beacons from different traffic flows around a roundabout.

road bends, we will see a significant percentage of large IPGs. With a beam width of 35° and the given vehicle traffic density, however, the IPG graph shows that the directional schemes are not overly affected by the given realistic bends. Because the correct epoch is eventually determined by the beacons from the immediately preceding vehicles beaconing in spatial order, the beam width relative to the road bend angle will not be a limiting factor in most roads, because the closely following vehicles will typically be covered by the directional beam while passing through the bends. Even if some vehicle V_x is inaudible to V_y for some time, if a vehicle (say, V_w) in front of V_y can hear V_x, V_y can easily determine its epoch. This is because V_w chooses its epoch based on V_x's beacon, and V_y has to follow V_w on the time axis based on V_w's beacon. Therefore, the lack of V_x's beacon does not affect the epoch selection of V_y. Even if there is no such intervening vehicle between V_x and V_y, Fig. 11 shows that the neighbors table is elastic enough to accommodate the fast topology changes created by sharp road bends. In Fig. 20, the best result is indeed obtained by the geographical scheduling algorithm. The omnidirectional communication scheme loses many more beacons than the directional schemes. Sent every 40 ms, only 60% of the beacons arrive without an intervening loss in the omnidirectional scheme. In comparison, the geographical scheduling algorithm manages to send over 90% of beacons without loss. Even in the realistic winding road environment, the major source of beacon losses is congestion, rather than the directional beam width. As long as we control the hidden terminal problem, directional communication can improve the message delivery rate while saving bandwidth for applications requiring directional semantics.

3.4.5. Vehicle flow on a roundabout

Probably the most challenging situation for the proposed method is a roundabout. This is because vehicles can receive beacons not only from the vehicles in front, but from other directions. In this case, the temporal beacon transmission ordering for a traffic flow can be temporarily disrupted. If a vehicle V_x in traffic flow F_i is scheduled to use epoch e_k approaches a roundabout, it can receive a beacon in e_k from a vehicle V_y in another traffic flow F_j. Without of loss of generality, suppose V_y begins beacon transmission in e_k first because its randomly generated jitter is smaller. Then V_x senses the busy channel, and backs off. This contention scenario is depicted in Fig. 22, where an "exogenous" beacon arriving from V_y on the roundabout contends with a beacon from an "endogenous" beacon to be transmitted by V_x. Within F_i, the loss of e_k has a cascade effect. Namely, V_x should use some epoch that has been scheduled to be used by a following vehicle V_w. If V_x wins, then V_w will have to contend with another following vehicle and so on. Not long after the exogenous beacon appearance, an internal collision between beacons from F_i results. This can be shown in the simulation below. The simulated roundabout topology is from the Columbus Circle, New York City. We obtained the mobile traffic model from the SUMO simulator of the topology, where we put 250 vehicles on and around the roundabout. Note that this traffic density is much lower than in previous experiments.

Fig. 23 shows the PDR result, and we confirm that the PDR in the geographical scheduling for the closest distances is slightly lower than the pure directional scheme in this roundabout topology. But the result should not be overemphasized because the dominant road topology is the linear strip. Also, applications such as cruise control typically stop when the driver applies the brake, which is highly likely to happen for a roundabout or an intersection. We can think that the

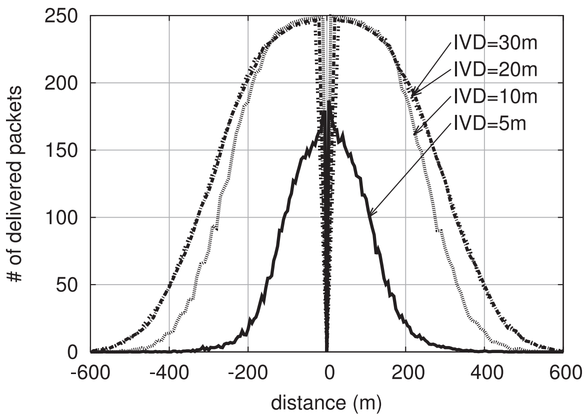


Fig. 24. Geographical scheduling applied to omnidirectional communication.

vehicles running on the open road can continue using the directional beaconing with geographical scheduling, whereas the blocked road vehicles resume using it when their road is open and vehicles begin moving again. As long as the beam is formed narrowly enough and a roundabout or an intersection is quickly passed, it will not cause major disruption to the proposed scheme. For longer distances, the geographical scheduling maintains its edge over the pure directional transmission.

3.4.6. Geographical scheduling in omnidirectional transmission

Finally, we investigate the benefit of geographical scheduling when directional communication is not supported. This is important, because almost all currently proposed safety applications assume omnidirectional communication [30], and only some applications such as CACC and communications from public safety vehicles (fire engines, patrol cars, ambulances) are expected to exploit directional transmission. Although we propose the technique to alleviate the problems of simple directional communication, omnidirectional communication is also improved as it coordinates the transmission schedules among neighboring vehicles. Fig. 24 shows the results of applying geographical scheduling to the case where all vehicles use only omnidirectional communication. We can see that, in the extremely congested scenario where IVD = 5 m, the result is similar to that for simple omnidirectional communication (Fig. 3(a)). However, for 10, 20, and 30 m, geographical scheduling leads to much higher packet delivery rates. Compared with directional communication using geographical scheduling, however, it handles the highly congested scenarios less well. Moreover, the channel resource use is much higher with omnidirectional communication, as we saw in Fig. 14.

4. Conclusion

In this paper, we explored the congestion control issue of directionally broadcast periodic safety messages. As directional transmission minimizes unnecessary traffic in the unwanted direction, we expected this to lead to reduced congestion and subsequently improved message delivery. However, we observed that directional transmission, when used alone, does not greatly improve the delivery performance, and can even worsen it. The reason for this disappointing phenomenon was confirmed to be the aggravated hidden terminal problem. We further found that, to minimize the adverse effects of hidden terminals, we should associate the temporal and spatial ordering of the message transmissions. Based on this finding, we designed a message scheduling algorithm that takes both into account. The proposed algorithm can be implemented at the application level using the existing information in exchanged beacon messages, such as the heading and vehicle position. Through extensive simulations of this application-level scheme, we have shown that directional transmission using the scheduling algorithm can achieve a significantly higher safety message delivery rate than omnidirectional messaging in the WAVE system. We also showed that the proposed scheme consumes less wireless resources, leaving more channel time to other applications.

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