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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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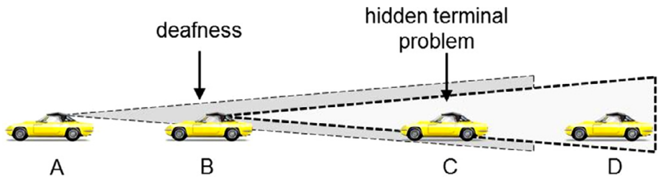

Fig. 1. MAC problems in directional beacon transmissions (B is the reference transmitter).

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 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.

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

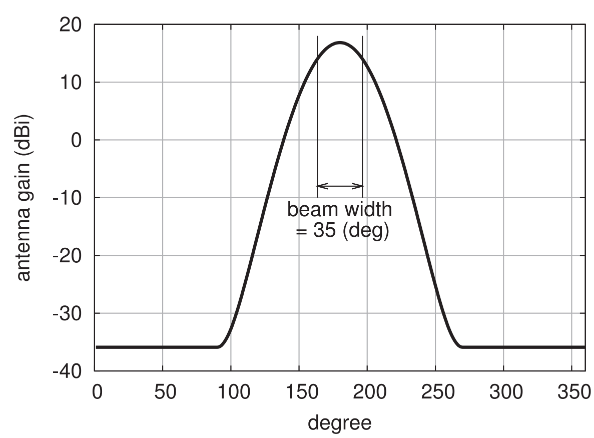

Fig. 2. Antenna pattern in directional transmission.