A New Interference-Aware Dynamic Safety Interval Protocol for Vehicular Networks[✝]

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Abstract   In IEEE 802.11p/1609-based vehicular networks, vehicles are allowed to exchange safety and control messages only within time periods, called control channel (CCH) interval, which are scheduled periodically. Currently, the length of the CCH interval is set to the fixed value (i.e. 50ms). However, the fixed-length intervals cannot be effective for dynamically changing traffic load. Hence, some protocols have been recently proposed to support variable-length CCH intervals in order to improve channel utilization. In existing protocols, the CCH interval is subdivided into safety and non-safety intervals, and the length of each interval is dynamically adjusted to accommodate the estimated traffic load. However, they do not consider the presence of hidden nodes. Consequently, messages transmitted in each interval are likely to overlap with simultaneous transmissions (i.e. interference) from hidden nodes. Particularly, life-critical safety messages which are exchanged within the safety interval can be unreliably delivered due to such interference, which deteriorates QoS of safety applications such as cooperative collision warning. In this paper, we therefore propose a new interference-aware Dynamic Safety Interval (DSI) protocol. DSI calculates the number of vehicles sharing the channel with the consideration of hidden nodes. The safety interval is derived based on the measured number of vehicles. From simulation study using the ns-2, we verified that DSI outperforms the existing protocols in terms of various metrics such as broadcast delivery ration, collision probability and safety message delay.

Key Words : WAVE, Multi-channel, Broadcasting, Beacon, VANET

1. Introduction

Intelligent transportation systems (ITS) refer to transportation systems which integrate advanced information and communication technologies into transport infrastructure and vehicles for enhanced transportation services. ITS provides a wide range of applications such as safety, security, congestion alleviation, environmental monitoring and protection, productivity and operational efficiency, comfort and convenience. Due to potential benefits from them, many academic institutes, automotive industries and governments around the world have paid increasing attention to ITS over the past few decades. ITS can take different underlying network architectures. A vehicular ad-hoc network (VANET) is one of well known network architectures to support many ITS applications. In a VANET, moving vehicles and road-side units create a self-organized mobile network without permanent infrastructure. VANETs

are characterized by high mobility and the restricted movement pattern governed by roads and traffic rules.

In IEEE 802.11p/1609[1] standards, seven 10 MHz-wide channels are available in the frequency band of 5.85-5.925 GHz: one control channel (CCH) and six service channels (SCHs). The channel access time is divided into synchronization intervals with a fixed length of 100ms. A synchronization interval is further divided into CCH and SCH intervals. Both intervals last $50ms$ long. According to the coordination scheme, all devices must stay tuned to CCH during the CCH interval in order to exchange safety and control messages. A device can actively switch from CCH to a specific SCH for its desired non-safety application services. However, the fixed-length intervals cannot be effective for dynamically changing traffic load. In a congested vehicular traffic condition, the fixed- length CCH may not be able to handle a large amount of safety packets and control packets. In addition, in sparse networks, the CCH channel can be wasted due to infrequent transmissions from vehicles. On the other hand, some applications consuming a large amount of bandwidth, such as video download and map update, cannot obtain sufficient SCH resources due to excessive contention. Therefore, dynamic interval division protocols have been proposed to address this problem [5], [6].

Existing dynamic interval division protocols commonly divide the CCH interval into safety and non-safety intervals. Safety messages such as periodic beacons are transmitted in the safety interval [4], and control messages such as a WAVE Service Announcement (WSA) message are transmitted in the non-safety interval. Since safety messages are life-critical, the safety interval precedes the non-safety one in existing protocols. After the safety interval is dynamically determined, the residual synchronization interval is divided into non-safety and SCH intervals. The ratio between the non-safety interval and SCH interval is dynamically adjusted to optimize a channel utilization. The length of safety interval is set to enough time to allow all nodes within the same contention domain[2] to successfully transmit their safety messages. In a single-hop network with one contention domain, there is no hidden node which can interfere the beacon transmissions within the safety interval. On the other hand, multi-hop networks such as VANETs suffer the interference from hidden nodes. In order to avoid the interference from hidden nodes, nodes hidden from each other should access the channel at different times. In other words, the safety interval should be shared by nodes within the same contention domain as well as nodes hidden from them, because hidden nodes may also transmit their beacons in the safety interval. However, existing protocols do not consider the presence of hidden nodes when they calculate the safety interval. Therefore, since there is no additional room to accommodate transmissions from hidden nodes in the safety interval, they cannot avoid interference from hidden nodes even though beacon transmissions are optimally scheduled within the given safety interval.

In this paper, we therefore propose a new interference-aware Dynamic Safety Interval (DSI) protocol considering the presence of hidden nodes. Since the safety interval should be shared by vehicles within the same contention domain and vehicles hidden from them, DSI allows each vehicle to accurately estimate the number of those vehicles. To achieve this goal, we first designs an estimating method over simple one-dimensional road scenarios

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[1] IEEE 802.11p [2] is an approved amendment to the IEEE 802.11 MAC/PHY standard to support wireless access in vehicular environments. The IEEE 1609 family of standards is a higher layer standard on which IEEE 802.11p is based [3]. Collectively, IEEE 802.11p and IEEE 1609.x are called wireless access in vehicular environments (WAVE) standards.

[2] A contention domain is a section of a network where data packets can collide with one another when being sent on a shared medium.

such as a straight highway and then extends the method to work over two-dimensional road scenarios such as urban streets. Finally, the safety interval is dynamically determined based on the estimated number of vehicles. The remainder of this paper is organized as follows. Related works on dynamic safety interval protocols for VANETs are presented in Section 2. Section 3 introduces the detailed description for the proposed DSI protocol. The DSI protocol is evaluated in Section 4. Finally, we conclude this paper with future work in Section 5.

2. Related works

In this section, we review existing works on the dynamic adjustment of CCH and SCH intervals. In particular, we focus on strategies for determining the safety interval within the CCH interval. To the best of our knowledge, Liu et al. [5] first proposed an adaptive MAC protocol, which is called Dynamic Interval Division Multichannel MAC (DID-MMAC), for the dynamic adjustment of CCH/SCH intervals. DID-MMAC further splits the CCH interval into three phases based on a type of different messages: Service Announce Phase (SAP), Beacon Phase (BP) and Peer-to-peer Reservation Phase (PRP). WSA and beacon messages are transmitted in SAP and BP, respectively and control message exchanges for SCH reservations are done in PRP. DID-MMAC assigns different channel access priorities to different messages by differentiating the inter-frame space (IFS) and the contention window (CW). Let us denote IFS and CW assigned to the beacon frame by IFS_B and CW_B, respectively. Therefore, BP (i.e. safety interval) ends when the idle time lasts during $IFS_B + CW_B \times slottime$ in the CCH interval. Consequently, BP in DID-MMAC becomes equal to the time required to allow all nodes within the same contention domain to successfully transmit their safety messages under a saturated traffic condition. In DID-MMAC, hidden nodes outside of a

given contention domain (CD) also transmit their beacons during their BP and BPs of nodes within and outside the CD may be overlapped in time. Therefore, transmissions from the safety interval are continuously exposed to the interference from hidden nodes.

Wang et al. [6] proposed a Variable CCH Interval (VCI) multichannel MAC protocol to enhance the saturation throughput of SCHs while ensuring the transmissions of safety messages. Similar to DID-MMAC, VCI also divides the CCH interval into safety interval and WSA interval. Periodic beacons are transmitted in the safety interval. During the WSA interval, service providers broadcast WSA packets and piggyback service information and the identities of SCHs to be used. Nodes that need the service can optionally respond to the WSA packet with an acknowledgement (ACK). In VCI, the length of safety interval (L_{safety}) is determined by Equation (1) where N represents the total number of nodes sending safety packets, B_{cch} is the data rate of CCH, α is a predefined factor according to current vehicular environment, and f is the sending frequency of safety messages.

$$L_{safety} = \frac{\alpha \cdot f \cdot N}{B_{cch}} \times 10^3 \quad (1)$$

In this equation, N is the only variable and L_{safety} is affected mainly by N. However, VCI does not mention how to calculate N in a dynamically changing traffic condition. Since VCI does not consider a network scenario with potential hidden nodes, N tacitly means the total number of nodes within the same contention domain. Therefore, VCI also cannot avoid interference from hidden nodes as in DID-MMAC.

3. DSI : Dynamic Safety Interval

In this section, our work is defined formally and the detailed description of the proposed DSI protocol is given.

Transmission range

Carreir-sensing /interference range
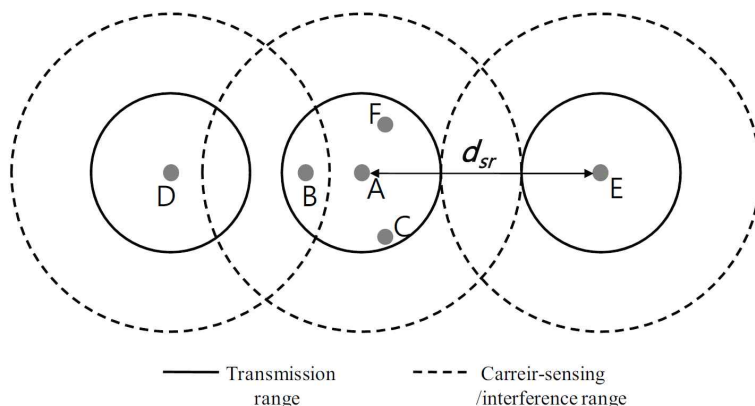
<Fig. 1> Hidden node problem.

3.1 design goal

DSI aims to allow the safety interval to accommodate transmissions from nodes within the same contention domain as well as nodes hidden from them. The region within which hidden nodes reside is affected by three types of ranges related to packet transmissions in the IEEE 802.11 MAC: Transmission range (r_t), carrier sensing range (r_c), and interference range (r_i). Here, r_t represents the range within which a packet can be successfully received by a node if there exists no interference from other nodes. r_t is mainly affected by the transmission power and radio propagation models. r_c is the range within which a transmitter triggers carrier detection. It is usually determined by the antenna sensitivity. r_i is the range within which nodes in a receiving mode are interfered with transmissions from other nodes. These ranges are tunable parameters which can significantly affect the MAC performance. Measurement studies such as [7] demonstrate that $r_t < r_i < r_c$. In addition, many studies assume that r_i and r_c are typically more than twice r_t [8]. In particular, r_i and r_c have default values of 2.2 times r_t in the ns-2 simulator. Assuming that the ratio of r_t to r_i is 1: R_{r_i/r_t} and the ratio of r_t to r_c is 1: R_{r_c/r_t}, R_{r_i/r_t} and R_{r_c/r_t} are considered as tunable system parameters. In this

work, we assume that R_{r_i/r_t} and R_{r_c/r_t} are equal to 2.2.

Hidden nodes refer to the nodes located within r_i of the intended destination and out of r_c of the sender. When a receiver is receiving a packet and a hidden node tries to start a concurrent transmission, collisions happen at the receiver. For example as shown in Figure 1, node B is located within interference ranges of both nodes A and D so that node D's transmission interferes with the transmission from node A to node B. On the other hand, node A's r_t is not overlapped with node E's r_i since nodes A and E are separated by a distance denoted by d_{sr}. Therefore, both nodes can concurrently transmit their packets without interfering with each other. d_{sr} is called a distance of spatial reuse and should be larger than the sum of r_t and r_i. In this work, we aim to allow each node i to share the safety interval with nodes whose distance from i is smaller than d_{sr}. We call the region where nodes sharing the safety interval reside extended contention domain (ECD).

In this work, we propose a protocol which calculates the number of vehicles within an ECD. Given the number of vehicles within the ECD, the optimal safety interval can be expected to be derived based on average contention delay and the link latency, which is our future work.
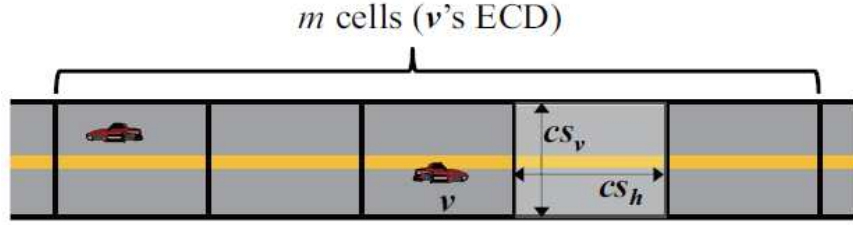
<Fig. 2> Extended contention domain and cellular structure (m=5).

3.2 Protocol design

The proposed DSI protocol is designed under following assumptions
- GPS & Digital map: It is assumed that each vehicle is equipped with a Global Positioning System (GPS) and a digital map. Each vehicle can identify its location over the map based on the GPS information.
- Periodic beacons: In VANETs, it is assumed that each vehicle periodically broadcasts its beacon including its current GPS position, velocity, braking/acceleration status, etc (approximately 10 times per second). Vehicles can become aware of their surroundings from periodic beacons received.

Each vehicle v can acquire the number of vehicles (n_{trx}) within its transmission range by collecting beacons from its neighbor vehicles. However, v cannot collect beacons from vehicles outside the transmission range of v but within the ECD centered at v (denoted by ECD_v) without relaying services from its neighbors. Therefore, DSI aims to calculate the number of vehicles within the residual part (denoted by $ECD_v - trx_v$) of ECD_v excluding the region covered by the v's transmission range (denoted by trx_v). DSI allows v to utilize vehicle density information such as n_{trx} which is measured by vehicles covering $ECD_v - trx_v$. However, since the transmission ranges of two vehicles A and B, which cover $ECD_v - trx_v$, can be overlapped with each other, the number of vehicles within the area covered by the overlapped transmission ranges is counted redundantly by A and B. Therefore, v cannot directly use n_{trx} which is measured by A and B, due to such redundancy for calculating the number of vehicles within the ECD. Consequently, DSI removes such redundancy in the n_{trx} measured by vehicles covering $ECD_v - trx_v$ and finally derives the number of vehicles within the ECD.

As shown in Figure 2, DSI subdivides the road into cells. Each vehicle v takes a role of measuring the number of vehicles within the cell (denoted by c_v) it belongs to. The measured $N(c_v)$[3] is disseminated to the vehicles whose ECD is overlapped with c_v. Finally, v acquires the number of vehicles within the ECD_v by adding the number of vehicle within each of cells overlapped with the ECD_v.

Parameters determining the cellular structure which covers the geographic area of the road are vertical and horizontal size of the cell denoted by cs_v and cs_h, respectively. Under the assumption that there is no vehicle outside of the road, cs_v can be simply set to the road width. On the other hand, cs_h is determined based on two constraints. The length of the diagonal of a cell should not be larger than r_t according to Constraint 1. In addition, under Constraint 2, the optimal cs_h is equal to $\sqrt{r_t^2 - cs_v^2}$.

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[3] We denote the number of vehicles with the cell named C by $N(C)$ in the rest of this paper.

- Constraint 1: In DSI, each vehicle v should accurately measure the number of vehicles within at least the cell it belongs to. Therefore, all vehicles within the cell which v belongs to should be within the v's transmission range.
- Constraint 2: The amount of information which a vehicle should collect decreases with the number of cells overlapped with ECD. Therefore, cs_h should be as large as possible in order to reduce the message overhead.

ECD covers up to m consecutive cells as shown in Figure 2, where m is equal to $\lceil \dfrac{2*d_{sr}}{cs_h} \rceil$. We call those cells ECD cells. Therefore, $N(c)$ measured by a vehicle within each cell c should be disseminated to the vehicles within cells (called target cells) which are separated by up to p number of cells in a horizontal direction from c, where $p = \left\lceil \dfrac{m-1}{2} \right\rceil$. To achieve this goal without using additional message exchanges, DSI allows $N(c)$ to be disseminated throughout target cells by piggybacking $N(c)$ on beacon messages according to the following description.

Given a specific cell c, we assume that the cells separated by (k-1) cells in a horizontal direction from c are called $cell_k$ and vehicles within $cell_k$ are called $cell_k$ neighbor vehicles ($k>0$). Similarly, c is called $cell_1$ by vehicles within c, and vehicles within $cell_1$ are called $cell_1$ neighbor vehicles. Under Constraints 1 & 2, a $cell_i$ neighbor vehicles cannot directly communicate with $cell_{(i+2)}$ neighbor vehicles. Therefore, as stated in [9], each vehicle should piggyback the set of the number of vehicles for $cell_i$ ($1 \le i \le p$) on its beacon. The information on the set is maintained in the local storage of each vehicle and is updated whenever the vehicle receives beacons from its neighbor vehicles as follows.

Algorithm 1 Updating local variables (m=5)

```
cell_s : the cell in which the sender is located.
cell_r : the cell in which the receiver is located.

if (cell_s == cell₁)  then
    update NBT
    for i = 1 to n do
        if i == (n+1)/2 then
            NA[i + 1] = max(num_erts, pNA[i], NA[i + 1])
        else
            NA[i + 1] = pNA[i]
        end if
    end for
else if (cell_s == cell₂) then
    for i = 1 to n do
        if cell_s is located on the left side of cell_r then
            if i == n then
                NA[i] = max(num_erts, pNA[i], NA[i])
            else
                NA[i] = pNA[i]
            end if
        else if cell_s is located on the right side of cell_r then
            if i == n - p then
                NA[i + 2] = max(num_erts, pNA[i], NA[i + 2])
            else
                NA[i + 2] = pNA[i]
            end if
        end if
    end for
end if
```

In DSI, each vehicle v maintains an array with m elements (called NA in this paper). Each element is indexed by $NA[i]$ $1 \le i \le m$ and stores the number of vehicles within its indexed ECD cell, where the number of vehicles located within the leftmost and rightmost ones among the ECD cells is stored at $NA[1]$ and $NA[m]$, respectively. NA is updated according to Algorithm 1 whenever v receives a beacon, and an array consisting of elements in NA excluding $NA[1]$ and $NA[m]$ (called pNA) is piggybacked on its beacon. Each element in pNA is indexed by $pNA[i]$ ($1 \le i \le n$, $n = m$-2). In addition, whenever a vehicle moves to the neighbor cell, it shifts the array one place to its moving direction.

When each vehicle v receives a beacon, it first checks the type of cell at which the sender is located. There can be two types of cell: $cell_1$ and $cell_2$. v processes the received beacon differently depending on the type of cell as shown in Algorithm 1. First, in case of $cell_1$, it first updates the table of $cell_1$ neighbor vehicles (called NBT).

Each entry in *NBT* consists of 2 fields: ID and the time at which *v* received the beacon. The beacon reception time is used to remove the outdated information in *NBT*. Under the assumption that a vehicle can receive a beacon more than once per second from each neighbor vehicle, DSI removes the information related to the vehicles undiscovered by *v* within a second. Consequently, the total number (denoted by *num_erts*) of table entries means the number of vehicles *v* discovered. After updating *NBT*, *v* updates its *NA* based on *pNA* piggybacked on the received beacon and *num_erts*. Under the assumption that *pNA* piggybacked on the most recently received beacon reflects the latest traffic situation, the value of each element in *pNA* is overwritten to its corresponding place within *NA* as described in Algorithm 1. Exceptionally, *num_erts* which vehicles in the same cell measure can be different with each other due to packet loss. Therefore, the biggest one among *num_erts*, $pNA\left[\left(\frac{n+1}{2}\right)\right]$ and $NA\left[\left(\frac{m+1}{2}\right)\right]$ is stored at $NA\left[\left(\frac{m+1}{2}\right)\right]$, where $pNA\left[\left(\frac{n+1}{2}\right)\right]$ indicates the number of vehicles in the cell *v* belongs to. Whenever a vehicle moves to the neighbor cell, it resets *num_erts* and $NA\left[\left(\frac{m+1}{2}\right)\right]$.

Second, in case of *cell₃*, *v* updates the *NA* based on *pNA* and *num_erts* without updating *NBT*. As described in Algorithm 1, the value of each element in *pNA* is overwritten to its corresponding place within *NA*.

3.3 An Extension to Two Dimensions

Vehicular environments can be categorized into two types: highway and urban environments. In previous sections in this paper, the DSI protocol which can be applied to simple one-dimensional road scenarios such as a straight highway has been proposed. Hence, the protocol could be extended for two-dimensional road scenarios such as urban streets. In this section, we discuss about how the DSI protocol can support two-dimensional urban environments.
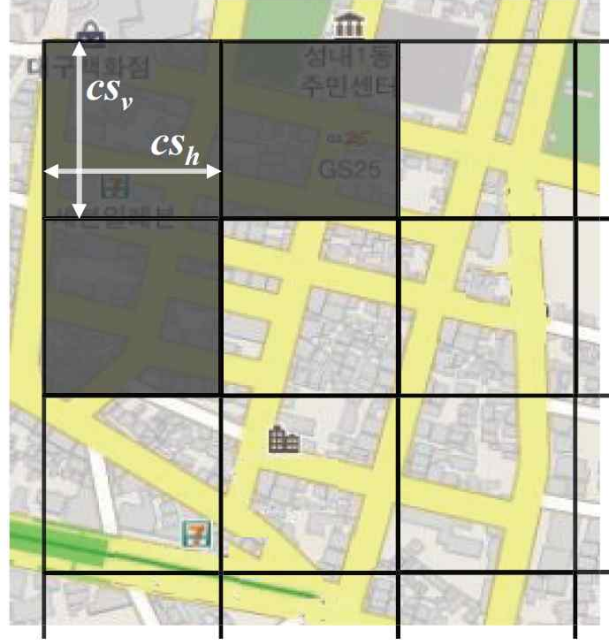
<Fig. 3> two-dimensional model.

In two-dimensional road scenarios, two or more roads either meet or cross at different angle, which means that vehicles hidden from a specific vehicle *v* may exist in any direction from *v*. Hence, the urban area including road segments should be divided into a grid of cells as shown in Figure 3. As mentioned before, the cellular structure is determined by cs_v and cs_h. Unlike the one-dimensional case, Constraint 1 and 2 should be applied to derive both cs_v and cs_h. First, regarding the Constraint 1, the diagonal length of a cell should be smaller than r_t, which results in the inequality $r_t \geq \sqrt{cs_h^2 + cs_v^2}$. Second, a diagonal length of a cell should be as large as possible in order to meet the Constraint 2, which results in the equality $r_t = \sqrt{cs_h^2 + cs_v^2}$. In addition, given a diagonal length of a cell, the region of the cell becomes the maximum when the

shape of the cell is a square, that is, $cs_v = cs_h$. Consequently, cs_v (= cs_v) becomes $\dfrac{r_t}{\sqrt{2}}$ by rearranging the two equalities $r_t = \sqrt{cs_h^2 + cs_v^2}$ and $cs_v = cs_h$.

Given the cellular structure, each vehicle measures the number of vehicles ($N(c)$) within the cell (c) it belongs to. And then, as stated in Section 3.2, the measured $N(c)$ is disseminated to the vehicles within target cells. In the one-dimensional case, target cells exist only in a horizontal direction from c. On the other hand, in the two-dimensional case, target cells can also exist in a vertical direction from c. More specifically, target cells (denoted by S_{tc}) are equal to the p x p grid of cells centered at a cell c.

All the vehicles in S_{tc} do not belong to the transmission range of a vehicle(v) within the cell c so that they cannot directly acquire $N(c)$ from v. Therefore, $N(c)$ should be disseminated to neighboring vehicles in multi-hop manner. As show in Figure 2, in one-dimensional scenarios, ECD covers up to m consecutive horizontal cells. On the other hand, in two-dimensional scenarios, ECD covers m consecutive horizontal & vertical cells. Therefore, $N(c)$ measured by a vehicle within each cell c should be disseminated to the vehicles within target cells which are separated by up to p number of cells in both horizontal and vertical directions from c, where $p = \left\lceil \dfrac{m-1}{2} \right\rceil$. This dissemination can be achieved by simply modifying the dissemination scheme described in the Section III. We omit the detailed description for the modification in this paper. Finally, we note that the message overhead of the dissemination scheme in two-dimensional road scenarios is certainly bigger than that in one-dimensional scenarios. Therefore, as the future work, we are planning to design a new dissemination scheme with low message overhead.

4. Performance evaluation

Performance comparisons were done using the most recent version of the ns-2 simulator (i.e. ns-2.35) [10]. From ns-2.31, ns-2 supports realistic wireless network environments with a new IEEE 802.11 model [11]. This model includes several new features, such as cumulative SINR computation, MAC frame capture capabilities, and supporting multiple modulation schemes, which ensures a significant higher level of accuracy. We made parameters defined in the MAC and PHY modules of ns-2.35 conform to the IEEE 802.11p standard. The probabilistic Nakagami propagation model was also used as the propagation model. Measurement studies indicated that the Nakagami model fits better to VANETs than other models [12]. In the Nakagami model, the distribution of signal strengths obtained by receivers can be controlled by a Nakagami fading parameter, ω. A smaller value of ω creates a more severe fading environment. In this simulation, we therefore set ω to 1 in order to create such a severe fading wireless environment. The transmission power used in the Nakagami model is set to 21.76dBm which is the transmission range (denoted by trx) of 250m under the deterministic Two-Ray Ground model. In addition, we set r_i to 550m, leading to R_{r_i/r_t} = 2.2.

In order to generate realistic movement patterns of vehicles, we used the USC mobility generator tool [13]. We generated a 2km long highway scenario. Our highway scenario consisted of 6 lanes (3 lanes for each direction with the lane width of 5m), in which N vehicles passed along the road with an average speed of 120km/h. N determines the density of vehicles. In order to evaluate the impact of change in the vehicle density on the performance, we defined three kinds of vehicle densities, N = 200, 400 and 800.

Our proposed DSI was implemented into the MAC module. In this performance study, we allowed DSI

(a) BDR vs. N.

(b) BDR vs. trx.
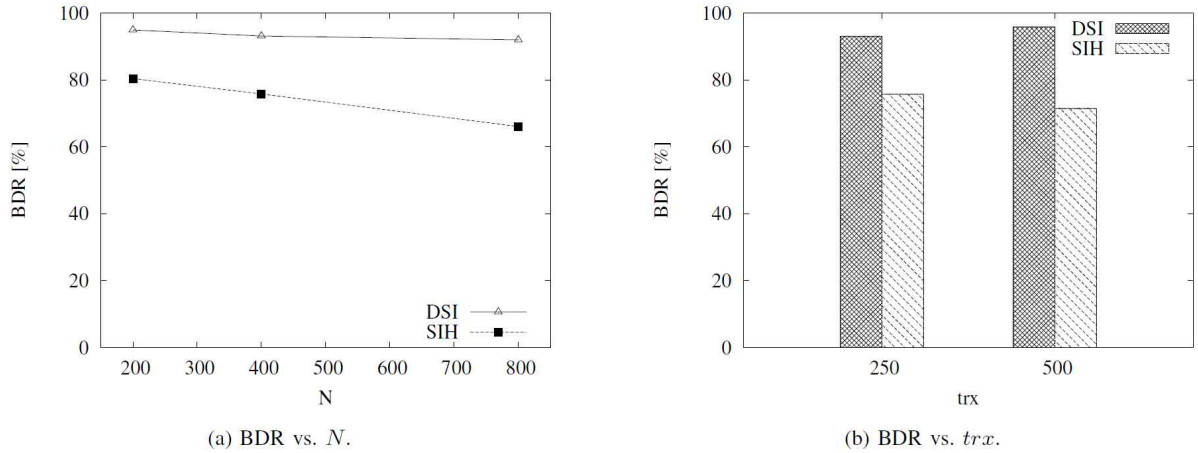
<Fig. 4> BDR comparisons.

to determine the length of safety interval (denoted by L_{safety}) according to Equation (2) where N is the number of vehicles sharing the safety interval, AIFS is the small time interval between subsequent beacon transmissions, γ is the average backoff time, and t_{trans} is the beacon transmission time. DSI sets N to the number of vehicles within ECD. The performance of DSI was evaluated against the protocol called Safety Interval without Hidden nodes (SIH). SIH allows each vehicle to calculate its safety interval based on the number of vehicles within its contention domain. For fair comparisons, SIH also calculates L_{safety} according to Equation (2). However, SIH sets N to the number of vehicles within the contention domain. Note that although Equation (2) used to derive the safety interval is not optimal, it can be used to evaluate the impact of the presence of hidden nodes on the safety interval. The optimal safety interval will be derived in our future work. Finally, we assume that the application generating beacons schedules its beacon transmission randomly based on a continuous random variable which is uniformly distributed between 0 and L_{safety}.

$$L_{safety} = N \times (DIFS + \gamma + t_{trans}) \quad (2)$$

Under the above-mentioned environment, we measured the performance of both protocols. The performance metrics of interest are summarized as below.

- Broadcast Delivery Ratio (BDR): the ratio of the number of receivers which have successfully received a broadcasted beacon to the number of receivers which are located within the transmission range of the sender. We measured BDRs of all vehicles and their averages are plotted in Figure 4.
- Collision Probability (CP): the probability that a collision occurs between beacon transmissions. A collision is defined as the event where the beacon transmission from a specific sender S is overlapped in time with the transmission from other senders within the ECD centered at S.
- Safety Message Delay (SMD): the time elapsed from the instant when the application issues a beacon message until the interface starts to inject the message into the channel.
- Message Overhead (MO): the ratio of the number of bytes in the information that must be sent with a beacon message for the desired operations of a protocol to the total number of bytes in the beacon message.

4.1 BDR

We measured BDR of both DSI and SIH according to vehicle density. From Figure 4a, it is observed that DSI outperforms SIH in terms of BDR regardless of the vehicle density. While L_{safety} of SIH includes no space for accommodating beacon

interfered with the transmission of a specific sender increases with the transmission range. Hence, the DSI's gain in BDR increases with the transmission range as shown in Figure 4b.

As mentioned in Section 3, L_{safety} is not optimal and any coordination scheme to avoid interference from hidden nodes is not used in this simulation

(a) DSI.

(b) SIH.
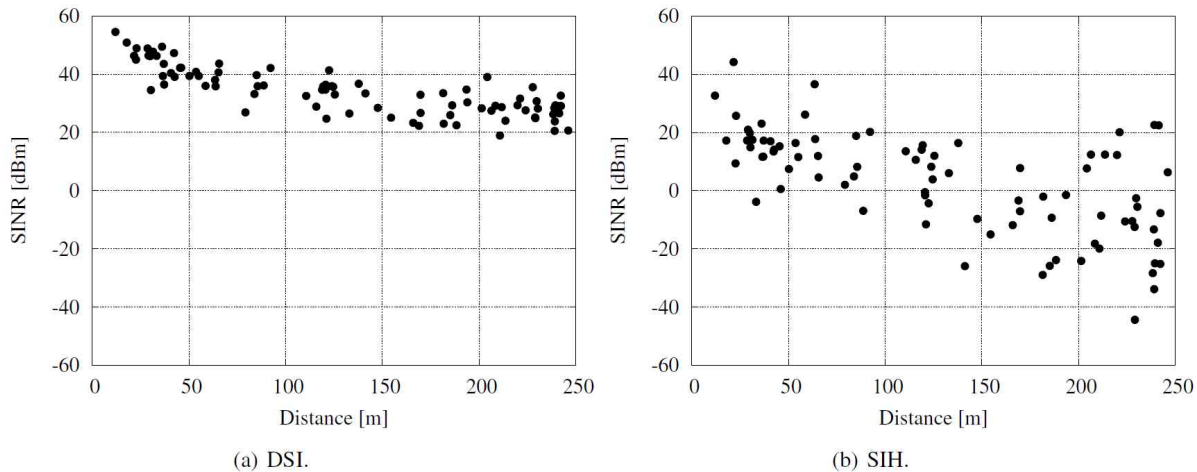
<Fig. 5> SINR distributions.

transmissions from the vehicles hidden within the same contention domain, L_{safety} of DSI is long enough to accommodate beacon transmissions from vehicles within the same contention domain as well as the hidden vehicles. Therefore, the probability that transmissions from vehicles hidden from each other become overlapped in time is lower than that of SIH, where DSI shows better BDR than SIH. In particular, the DSI' gain in BDR increases with the vehicle density as shown in Figure 4a. This is because the number of hidden nodes whose transmissions are overlapped with the transmission from a certain sending node increases with the vehicle density. In Table 1, we summarized the performance gain that DSI achieved.

We also measured BDR of both protocols with various transmission ranges. In this simulation, N was set to 400. Under the fixed vehicle density, the number of hidden nodes whose transmission can be

study. However, note that DSI can show better performance in terms of BDR under the optimal safety interval and a coordination scheme.

<Table 1> DSI's gain in BDR.

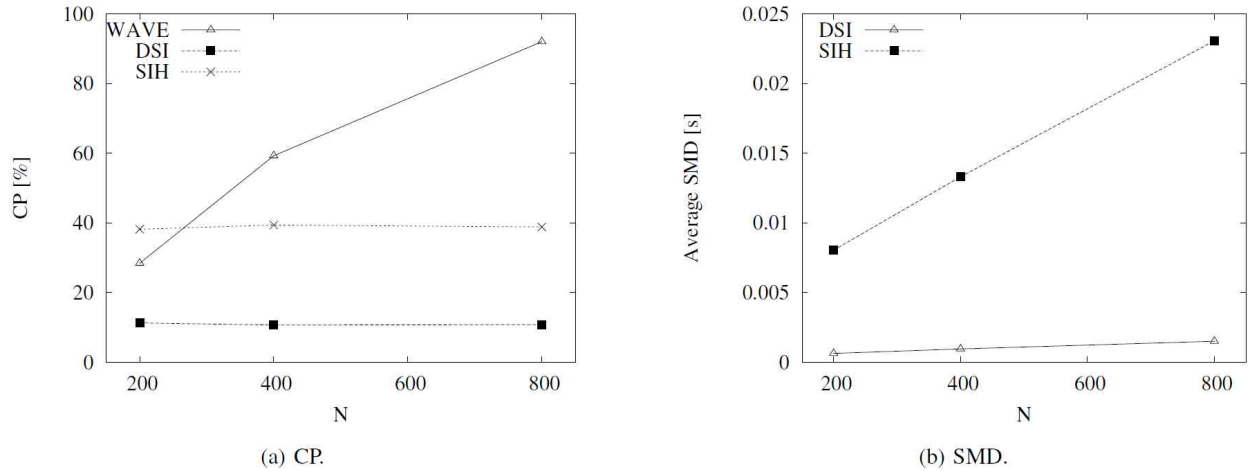|	N=200	N=400	N=800
DSI's gain	14.6%	17.3%	26.1%

Figure 5 shows the accumulated strength of signals from hidden nodes interfering each beacon reception of vehicles within transmission range of a specific sender. N and r_t were set to 800 and 500, respectively in this simulation. As expected, DSI shows a significant decrease in signal-to-interference -plus-noise ratio (SINR) as compared to SIH. SINR is the ratio of the received strength of the desired signal to the received strength of undesired signals (noise and interference).

4.2 CP

BDR is mainly affected by three parameters: the MAC-layer contention, capture and sensing capabilities, channel quality. The first one is the only parameter which can be controlled by MAC protocols, while the others are related to the physical-layer properties. Existing measurement studies indicated that packet collision happens more frequently as the degree of MAC-layer contention becomes heavier. Therefore, we measured the collision probability to evaluate the degree of

4.3 SMD

Figure 6b depicts the average SMD performance of both protocols according to the vehicle density. The safety interval of SIH includes no space for accommodating beacon transmissions from hidden nodes. Hence, due to the heavy MAC-layer contention, some beacon transmissions issued in a specific safety interval are deferred and become scheduled in the next safety interval, which leads to additional delay. On the other hand, DSI can significantly shorten the average SMD as compared

<Fig. 6> CP and SMD comparisons with various vehicle densities.

reducing contention that DSI can achieve. CPs of DSI, SIH and WAVE are measured in this simulations. The WAVE protocol uses the safety interval that lasts 50*ms* long. As shown in Figure 6a, DSI shows approximately *30*-percent lower CP than SIH regardless of the vehicle density due to the reduced MAC-layer contention. In addition, we observe that the DSI's gain in CP as compared to WAVE increases with the vehicle density. This is because the MAC-layer contention becomes more severe as the number of vehicles trying to transmit beacon messages within the given safety interval increases.

to SIH, since it provides the safety interval long enough to accommodate all the beacon messages from the vehicles within the same ECD. In particular, since the MAC-layer contention increases with the vehicle density, DSI shows a lower average SMD as compared to SIH in heavier traffic scenarios.

4.4 MO

When R_{r_i/r_t} = 2.2, the total number of ECD cells (*m*) becomes 7, and DSI allows the information of 5(*m*-2) bytes to be piggybacked on

every beacon message as stated in Section 3.2. The increase in the size of beacon messages affects BDR and CP of beacon transmissions. Hence, we measured BDR and CP according to the size of the beacon message. According to the simulation results, the 5-byte increase in the payload leads to at most 0.5% decrease in BDR and 1.2% increase in CP when the vehicle density is high (i.e. N=800). The margin of performance degradation decreases with the vehicle density. Consequently, we clarify that the performance degradation caused by message overhead is considered very slight as compared to the DSI′s gain in BDR and CP.

5. conclusion

In this paper, we proposed a new interference-aware Dynamic Safety Interval (DSI) protocol. In multi-hop VANETs, the channel should be shared evenly by vehicles hidden from each other. In order to avoid potential interference from such hidden nodes, DSI allows the safety interval to accommodate transmissions from vehicles within the same contention domain as well as nodes hidden from them. To achieve the goal, DSI measures the number of vehicles (N) in an extended contention domain (ECD) within which vehicles hidden from each other can exist. Therefore, the length of safety interval (L_{safety}) can be dynamically determined based on N. We measured the performance of DSI against the Safety Interval with Hidden nodes (SIH) protocol which calculates L_{safety} based on the number of vehicles within the same contention domain without considering the presence of hidden nodes. DSI outperforms SIH in terms of Beacon Delivery Ration (BDR), regardless of the vehicle density and the interference range of the radio. In particular, in dense network scenario, DSI achieved 26.1% performance improvements of BDR than SIH. In the future work, we are planning to derive the optimal safety interval based on N.

Acknowledgments

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