

## A Performance Study of Inter-Vehicle Communication Protocols for Collision Warning System

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Collision Warning Systems (CWS) can help reduce the probability and severity of car accidents by providing some sort of appropriate warning to the driver through Inter-Vehicle Communication (IVC). Especially, the CWS can help avoid collision at intersections where traffic accidents are frequent (Study Group for Promotion of ASV; Traffic Bureau, 2007). A vehicle equipped with the CWS periodically broadcasts its information, and the CWS on other vehicles use the received information to alert drivers, helping them become aware of the existence of other vehicles. To avoid collision, the CWS has concrete objectives of IVC, i.e., the CWS should receive useful information accurately and in time. Many IVC protocols including our previously proposed relay control protocol (Motegi, et al., 2006) have been developed and evaluated through traditional metrics. However, instead of using such traditional metrics directly, many requirements of the intersection CWS must be considered to judge the feasibility and practicability of IVC protocols. This paper shows performance evaluation of our previous IVC protocol developed for CWS. To study the behavior of IVC protocols, we first describe a simulation methodology including performance metrics by means of reliable and timely communications. We then use such metrics to compare our IVC protocol with the flooding protocol in large-scale simulated networks. The simulation results show that our previously proposed protocol is a good candidate for real implementation because it passes all requirements of the intersection CWS.

### 1. Introduction

Inter-Vehicle Communications (IVC)<sup>2),4),12)–14),20)</sup> are going to create new services by transmitting packets from vehicle to vehicle without the use of any deployed infrastructures. One of the promising services is Collision Warning System (CWS) which aims for a safe and comfortable drive by tracking the movements of other vehicles. Vehicles transmit necessary data such as the current location, the motion's direction, and the speed for tracking purposes and the CWS provides appropriate alerts or navigation to drivers, helping them become aware of the existence of other vehicles that are approaching the same intersection from other directions, even if these vehicles are out of sight.

Vehicles equipped with the CWS come across many vehicles on their way and need to provide their own data promptly to other vehicles. The Carrier Sense Multiple Access (CSMA) is suitable for Media Access Control (MAC) of the IVC because it allows distributed media access<sup>20)</sup> and all data packets are broadcasted. It is also important to maintain the freshness of data because the locations of moving vehi-

cles continuously change with the time. This means *reliable* data deliveries are required for the CWS, and data must be delivered *timely*, for example within 100 ms. To achieve reliable delivery, a typical MAC mechanism like Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) attempts to avoid collisions by exchanging control messages. However, this increases communication delays, due to the considerable overhead caused by exchanging messages with every neighbor for every data transmission. Another approach is a consecutive transmission that transmits the same packet several times<sup>20)</sup>. Even if we used this approach, in the actual environment, there are many cases where vehicles would be unable to communicate with each other due to the presence of obstacles and/or being outside the range of wireless transmission and so on.

Therefore, relay control protocols for the IVC have been proposed to provide indirect communications through packet relaying by other vehicles. Although the relay expands the area where packets can be delivered, it introduces new communication overheads. Wireless bandwidth is a limited resource; therefore, increasing the communication traffic causes large communication delays, meaning it gets more difficult

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to keep the data up to date.

Intersection is the target of our study because drivers are unable to see vehicles approaching the same intersection from other directions due to obstacles, especially the large number of buildings in urban areas. Moreover, an intersection is a place where drivers often violate traffic regulations. It is reported that half of the deaths (21,000 of the 43,000) per year on America's highways are caused by departures at intersections and other related incidents<sup>8)</sup>. Japanese National Police Agency also reported that nearly 70% of road accidents (517,000 of the 761,000) are rear-end collisions around intersections<sup>21)</sup>. Therefore, the intersection CWS is a promising service to bolster drivers' safety.

Previous works on both mobile ad hoc networks and IVCs used traditional metrics, e.g., the packet delivery ratio, the average delay, and the path optimality, to study the performance of protocols. However, such metrics are not appropriate for our evaluation because the identities of the prospective receivers are a priori unknown. Moreover, many requirements must be considered to judge whether an IVC protocol satisfies the objectives of the intersection CWS. Even if a vehicle gets information properly, it becomes useless if that information arrives too late. Thus we describe the metrics and the simulation methodology at first, and then carry out the performance evaluation of our previously proposed IVC protocol<sup>13)</sup> for the intersection CWS. We compare the performance of our protocol with that of the flooding protocol through large-scale simulated networks. The performance evaluation also validates the logic of the proposed protocol and can be used as a guideline to choose a protocol for real implementation.

The remainder of the paper is organized as follows. Section 2 discusses related work. Section 3 provides an overview of our previously proposed protocol, the relay control protocol. Section 4 describes the performance metrics used for evaluating IVC protocols. Section 5 presents the methodology to perform realistic evaluations through simulations. Section 6 reports the results of the simulation. Conclusion and Future works are discussed in Section 7.

## 2. Related Work

At first, we need appropriate metrics to evaluate IVC protocols. Various kinds of perfor-

mance metrics such as the packet delivery ratio, the average delay, the path optimality, and the normalized routing load have been widely used to study the protocols developed for Mobile Ad Hoc Network (MANET)<sup>3),5),15)</sup>. Such metrics are also used in the literature on IVC<sup>4),12),14)</sup>. However, we cannot simply apply those traditional metrics to the intersection CWS because the identities of the prospective receivers are a priori unknown.

We must first define a target receiver before the packet delivery ratio can be calculated correctly. Ko and Vaidya<sup>11)</sup> proposed the idea of using geographic constraints to specify the target receivers when evaluating location-based multicast protocols. Briesemeister, et al.<sup>2)</sup> also used the same idea by defining the zone-of-relevance which extends beyond the region of the highway where the accident occurs. However, they did not specify the radius of the zone-of-relevance which is an important parameter when evaluating IVC protocols. The performance study was done on a rectilinear road where a group of vehicles are always moving together in the same direction. If an intersection occurs, a vehicle may change its direction and move away from others. Therefore, we recommend to include as many road components as possible in order to evaluate the exact performance of IVC protocols for the intersection CWS (Section 5).

The delay is an important metric for IVC protocols due to the high motion speeds of vehicles, especially the vehicles on expressway or super-highway. Instead of a simple average delay, we can calculate the delay in other ways. For example, Naumov, et al.<sup>14)</sup> proposed to use the average delay of a first data packet. However, drivers do not need to receive packets from all vehicles in a city or country. Therefore, we should count only the necessary packets, not all of the packets. Moreover, it becomes useless if a packet arrives too late. Thus, an upper bound of the delay should be considered in order to determine the timeliness of the data packets.

## 3. Overview of Relay Control Protocol

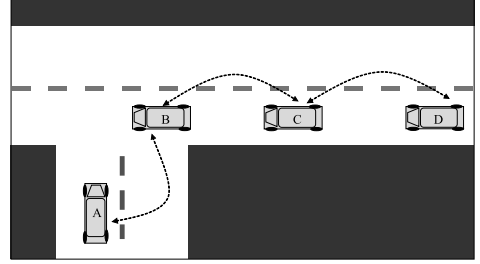
We briefly describe our relay control protocol<sup>13)</sup> developed for IVC. The protocol provides indirect communications for vehicular networks by relaying a packet from vehicle to vehicle. Each vehicle is assumed to have a unique address and all vehicles periodically broadcast a packet containing the location, the direction,

the speed and so on. The packet header contains all necessary control informations, i.e., an individually distinguishable source address, a sequence number, and a hop count. The proposed relay control protocol aims to reduce delays and the probability of packet collision by reducing the communication traffic. To achieve such aims, a vehicle relays received packets based on necessity, i.e., the proposed protocol starts and stops the relay by adapting to various communicative environments of vehicles. Moreover, the proposed protocol prevents any unnecessary communication traffic by avoiding duplicate relays through a Duplicate Relay Detection (DRD) algorithm, which runs with minimal overhead because little extra data are added to a normal packet.

### 3.1 Trigger Points of Packet Relay

To reduce the communication traffic generated by relays, the proposed protocol starts the relay based on necessity. In other words, the protocol does not relay other vehicles' packets unless it is required. This contributes to reducing communication traffic compared to the flooding protocol, in which all vehicles relay packets. Consequently, the proposed protocol achieves shorter communication delays, since the vehicles have free access to the media.

There are two typical cases (I) and (II) in which a request is generated. For the case (I), a request is generated if the wireless quality of a neighboring vehicle deteriorates. The quality degradation can be detected from received wireless transmission levels and/or packets reception rates. When a vehicle detects the deterioration, it adds a request signal (REQ) to a normal broadcasted packet to request relays from neighboring vehicles. The REQ contains *req\_addr* and *req\_src\_addr*. *req\_addr* is the address of the neighbor, whose packets are requested for relay by the vehicle. *req\_src\_addr* is the source address of this request. When a vehicle receives a packet including the REQ signal and if it also receives the packet requested by the REQ signal, it starts relaying the packet. When the vehicle starts the relay, it adds a reply signal (REP) to a normal broadcasted packet. The REP contains *req\_addr*, *req\_src\_addr*, *rep\_src\_addr* and *hop*. *req\_addr* and *req\_src\_addr* are copied from the received REQ. *rep\_src\_addr* is its own address. *hop* is the number of hops from *req\_addr* (the neighbor whose packets are requested) to itself. In addition, the vehicle maintains a *req\_list* for each



**Fig. 1** The driver in vehicle D is not aware of the existence of vehicle A due to obstructions at the corner of the intersection. Vehicle B and/or C can help relay A's packet to vehicle D.

*req\_addr*, i.e., *req\_list[req\_addr]*. The *req\_list* keeps the *req\_src\_addr* requesting the relay of packets generated from *req\_addr*. After sending the REP response, the vehicle adds *req\_src\_addr* to the *req\_list[req\_addr]*.

The relay in case (II) starts when a vehicle meets new vehicles. In this case, the vehicle starts relaying packets of its current neighboring vehicles to the newly met vehicles. For example, vehicles B and C in **Fig. 1** are moving in the same direction from right to left, and are receiving packets from each other. When vehicle B approaches an intersection, it meets vehicle A, which is approaching the same intersection from another direction. Vehicle B can detect vehicle A by receiving packets from A. The detection is a trigger to start relaying the packets of vehicle C. When vehicle B starts the relay, it responds with a REP, as in the case (I). However, in this case, vehicle B does not receive the REQ from vehicle A, since vehicle A does not send it. The REP contains *req\_addr* and *req\_src\_addr*. Vehicle B specifies the source address of the relayed packet (the address of vehicle C in this example) in the *req\_addr* field of the REP. The address of the newly met vehicle A is specified in the *req\_src\_addr* field of the REP. Finally, vehicle B adds the address of vehicle A to the *req\_list[C]*. The REP is also used in the DRD algorithm described in the next section.

### 3.2 Duplicate Relay Detection Algorithm

In this section, we describe the duplicate relay detection algorithm, which uses the REP signal. **Figure 2** shows the flow of the DRD algorithm. The REP is added to a data packet and sent when vehicles start to relay. The REP contains informations which imply the intention of the relay, namely, which packet (*req\_addr*) is

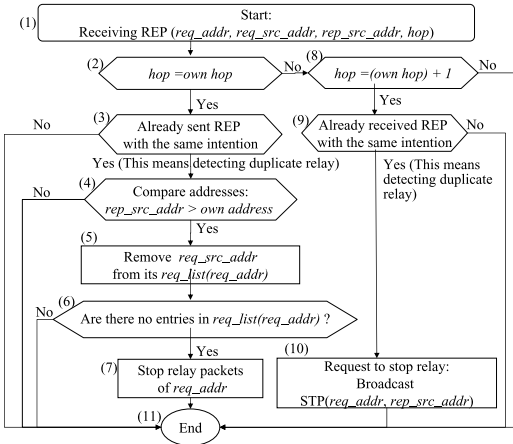
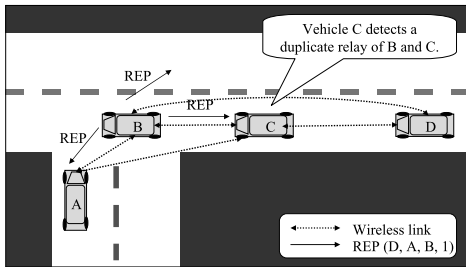
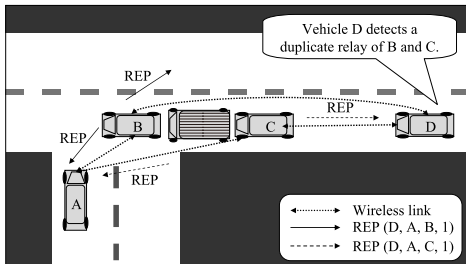


Fig. 2 Flow of duplicate relay detection algorithm.



(a) Duplicate relay detection by overhearing.



(b) Duplicate relay detection by upstream vehicle.

Fig. 3 Examples of duplicate relay detection.

relayed toward who (*req\_src\_addr*). Using the REP, vehicles can detect the duplicate relay in order to avoid the possibility of the same packets being relayed by multiple vehicles. Based on a packet header that contains a source address and a sequence number, vehicles avoid the possibility of duplicate relays.

To detect duplicate relays by multiple vehicles, vehicles check a received REP, which implies the intention of the packets relay. If this is the same as its own relay, the vehicle registers it as a duplicate relay. For example in Fig. 3 (a), vehicles B, C and D are moving in the same direction from right to left. Subse-

quently, vehicles B and C meet vehicle A at the same time and broadcast packets including a REP message to relay their neighbor’s packets for vehicle A. Vehicles B and C add the address of vehicle A to their own *req\_list[D]*. Since vehicles B and C relay the same packets toward vehicle A, the algorithm detects duplication as follows.

Vehicle B checks whether the distance (hop count) between vehicles C and D is the same as its own (Fig. 2 (2)). If the hop count is the same, vehicle B checks whether the intention of the packets relay, implied by the received REP, and that of its own packets relay are the same or not (Fig. 2 (3)). If the intention is the same, the vehicle B registers these as duplicate relays. Likewise, vehicle C also detects the duplication. By comparing the addresses, vehicle C, whose address is smaller than that of vehicle B for example, goes to the next step to stop the relay (Fig. 2 (4)). Vehicle C removes the address of the vehicle A from its *req\_list[D]* (Fig. 2 (5)). Consequently, vehicle C knows there are no vehicles to request the relaying, since there are no entries in *req\_list[D]* (Fig. 2 (6)), and thus stops relaying packets of vehicle D (Fig. 2 (7)).

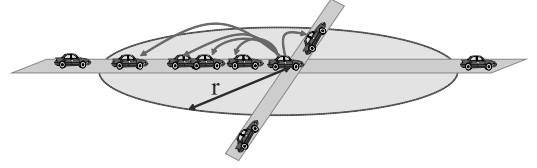
In addition to the above case, in which relaying vehicles can receive a REP from each other, the DRD algorithm also copes with hidden terminal problems where relaying vehicles cannot receive a REP. For example in Fig. 3 (b), three vehicles, B, C and D, are moving in the same direction and vehicles B and C meet the vehicle A. Vehicles B and C add a REP to their normal broadcasted packets. In this example, it is difficult for vehicles B and C to receive packets of each other due to the existence of obstacles (e.g., bulky vehicles, trucks), hence they are unable to detect duplicate relays because they do not receive each other’s REP. Therefore, in this case, the vehicle D, which is an upstream vehicle of packets relayed by vehicles B and C, detects the duplicate relay because it receives REPs from vehicles B and C (Fig. 2 (8) and (9)). When vehicle D detects the duplicate, it adds a stop signal (STP) to its normal broadcasted packet (Fig. 2 (10)). The STP contains the address of the vehicle requested to stop the relay, *req\_addr*, and *req\_src\_addr*. The STP is also used when the requested relay becomes unnecessary due to changes in the communication environments.

#### 4. Performance Metrics

Information distribution around the vicinity of an intersection is important and helpful because a driver might not be aware of vehicles that are approaching the same intersection from other directions if buildings exist as obstructions at corners of the intersection. As shown in Fig. 1, the driver in vehicle D is not aware that the vehicle A is approaching the same intersection, and vice versa. If the traffic light did not exist, accidents would likely occur at the intersection according to the report<sup>8),17)</sup>. With the assistance of vehicle B and/or C in relaying packets, the driver D can know the existence of vehicle A, and vice versa. This section describes the metrics used for evaluating IVC protocols for the intersection CWS. The metrics are based on the requirements discussed in the Advanced Safety Vehicle (ASV) project<sup>17)\*1</sup>. We note that a study on a rectilinear road is less pertinent than at an intersection because a driver has clearer and wider vision on a straight road. Driving automations and sensor-based systems also satisfactorily assist drivers on rectilinear roads in comparison with intersections.

##### 4.1 Conditional Reception Rate

As discussed above, the identities of the prospective receivers are a priori unknown and frequently change with the time due to the high mobility of vehicles. To study IVC protocols effectively, we must know the receivers, i.e., unrelated receivers must be excluded from the evaluation. Therefore, we recommend using an *intersection zone* to determine the *target vehicles* which are supposed to receive the packets. The intersection zone is a circular region centered on the central point of the intersection with a radius of  $r$  meters. The radius  $r$  is set to 200 meters in our evaluation according to the extensive study of the ASV project. To achieve the purpose of safe driving, the packet sent from any vehicle in the intersection zone must be received by all vehicles which are currently inside the same intersection zone at the time of packet transmission. As shown in Fig. 4, six vehicles



**Fig. 4** Each vehicle in the intersection zone (circular region) must receive information from the others in the same intersection zone.

inside the intersection zone must get information from the others. We note that an evaluation pays attention to one intersection at a time, i.e., the intersections are evaluated separately one by one. Another requirement discussed in the ASV project is that of the delay. Every packet from a target vehicle must arrive at other target vehicles within  $t$  ms, where  $t$  is set to 100 ms in our evaluation. Thus, the conditional reception rate of the packet  $i$  initiated inside the intersection zone is calculated by Eq. (1).

$$R_i = \begin{cases} 0, & \text{if } N_{z_i} = 1 \\ \frac{N_{r_i}}{N_{z_i} - 1}, & \text{otherwise} \end{cases} \quad (1)$$

$N_{z_i}$  is the number of vehicles inside the intersection zone when the packet  $i$  is sent from a vehicle in the same intersection zone. The number of vehicles which is supposed to receive the packet  $i$  is  $N_{z_i} - 1$ , i.e., all the vehicles in the zone except the sender.  $N_{r_i}$  is the number of vehicles which actually receive the packet  $i$ .

The conditional reception rate of an entire experiment is determined by Eq. (2).

$$R = \begin{cases} 0, & \text{if } \sum_{i=1}^{all} (N_{z_i} - 1) = 0 \\ \frac{\sum_{i=1}^{all} N_{r_i}}{\sum_{i=1}^{all} (N_{z_i} - 1)}, & \text{otherwise} \end{cases} \quad (2)$$

The conditional reception rate in Eq. (2) is a ratio between the number of all target packets which are actually received and the number of all target packets which are supposed to be received. Note that a packet whose delay is longer than the delay requirement ( $t = 100$  ms) is marked as a failed reception, although it arrives at the target receiver correctly. The conditional reception rate is a useful metric to determine the *reliability* and the *timeliness* of an IVC protocol.

##### 4.2 Average End-to-End Delay

The average end-to-end delay is an important metric for evaluating the performance of IVC protocols in details because protocols that send a large number of duplicated data packets

\*1 A study group for promotion of Advanced Safety Vehicle was organized by Road Transport Bureau, Ministry of Land, Infrastructure and Transport, Japan in 1996, with members from 13 vehicle manufacturers including trucks, buses and motorcycles, officers from relevant ministries and agencies, and experts from academic field with professional experiences.

and routing packets can also increase the probability of packets collisions and may delay data packets by queuing them in the buffer. Delay calculation is based on the same concept as the conditional reception rate in order to achieve safe driving purpose. In particular, we consider only packets that are sent from vehicles lying inside the intersection zone. The target receivers are the vehicles lying inside the same intersection zone at the time of packet transmission. End-to-end delay is observed between transmitting a data packet and receiving it at the target vehicles. We calculate the average end-to-end delay of actually received packets to determine how fast the protocol can transmit data considering to the above requirement ( $t = 100$  ms). Packets that take longer than 100 ms are also included in the calculation.

### 4.3 Transmission Overhead Ratio

Vehicular information is distributed through relay packets which means that the same packet is retransmitted multiple times. It is difficult to determine a relay node because more relay nodes help extend the range of information distribution but relay packets can be considered as transmission overhead. The vehicle density is very high at an intersection when the traffic light turns red. The probability of collision increases sharply if the number of relay nodes is high in such a situation. Therefore, we count relayed packets which are duplicated packets as the transmission overhead. The number of routing packets is also included in transmission overhead. To normalize the value of the transmission overhead, the ratio between the transmission overhead and the number of originally generated packets is calculated as the transmission overhead ratio.

## 5. Realistic Evaluation Methodology

The following methodology is a guideline to perform a realistic evaluation through a simulation. In our experiments, we used the release 2.30 of ns-2 simulator<sup>(6),19)</sup>. The ns-2 simulator was validated<sup>(10)</sup> and verified in a number of publications<sup>(3),5),12),14),15)</sup>. We first discuss the properties of realistic vehicular traces and describe the trace used in our study. We then report appropriate simulation models and parameters based on the requirements and suggestions determined by the ASV project and the ITS Forum<sup>9)\*1</sup>.

### 5.1 Vehicular Traces

The random waypoint model<sup>(3)</sup> which is a fa-

vorite mobility model of MANET researchers is far from actual vehicular movements. This model is considered harmful for evaluating MANET protocols because it fails to provide a steady state in that the average nodal speed consistently decreases over time<sup>(22)</sup>. It is reported by the above literature that the result obtained by using this model is unreliable. Moreover, the previous work showed that the results of performance studies of ad hoc networks depend heavily on the chosen mobility model<sup>(1)</sup>. Furthermore, all MANET mobility models<sup>(3),7),24)</sup> fail in evaluating IVC protocols because they do not consider road parameters like the lane configuration, the traffic light, and other factors. Consequently, we prepared realistic vehicular traces separately, and then imported them into the network simulator (ns-2) for evaluating large-scale scenarios.

Vehicles must move along the road which may be a main road or a branch road depending on the number of lanes. In addition to simple movements like going straight along the road, our movement model includes complex maneuvers like lane changes or overtaking. It means we include as many factors in the model as possible. The route choice of each driver is affected by lane configurations such as the number of lanes, the existence of a right turn lane, and the directional regulation for each lane, and it is also affected by dynamic traffic informations such as the change of traffic light and the surrounding vehicles. Note that not only intersections of two roads but junctions of three roads or five roads also exist on our road map. All kinds of intersections are considered to evaluate the intersection zone.

The above vehicular movement is created as follows. First, a digital map is a prerequisite for the vehicular movement. Currently, it is easy to get maps from many sources such as Google Maps<sup>\*2</sup>, Yahoo! Maps<sup>\*3</sup>, field works, etc. We collected road informations of major cities in Japan from such multiple sources. The road informations are composed of various characteristics and attributes of road components such as

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\*1 The ITS Info-communications Forum was established to promote evolution of the roadway, transportation and automotive fields using highly advanced intelligent transport systems, with a special focus placed on research, development and standardization of information-communications technologies.

\*2 <http://maps.google.com>

\*3 <http://maps.yahoo.com>

locations (coordinates), lanes, curves, intersections, traffic lights, traffic rules (e.g., one-way traffic), and so on. Based on such informations, we created the digital map whose main components are roads (links), intersections (nodes), and traffic lights. Intersections (nodes) are connected by roads (links), and traffic lights are placed at some intersections. Roads are further divided into lanes (including right turn lanes) according to the collected informations. Lanes are used to determine the road's capacity which means the maximum number of vehicles that the road can serve. It is explicit that more lanes can serve a higher number of vehicles. The digital map uses Cartesian coordinates whose (0, 0) coordinate is set to lower-left corner of the map by default.

After the digital map is ready, the next step is to prepare vehicular movements or traces through a traffic simulator. The main inputs of the traffic simulator are the following sets of data: the digital map, the starting points, the destinations, and the possible routes. The timing and the sequence of each traffic light which is collected along with the road informations are also inputs of the traffic simulator. The traffic simulator determines the starting point, the destination and the default route of each vehicle. Though each vehicle runs from its starting point to the destination along the default route, it changes to a new route on-the-fly depending on the current situation of the surrounding traffic. The route decision algorithm is developed from the analyzed results of questionnaires answered by drivers. The results of the route decision algorithm must match driving facts, e.g., the total traffic must be less than or equal to the capacity of each road. Thus the traffic simulator is run to create vehicular traces. Then the digital map and the vehicular traces are provided as inputs of the network simulator (ns-2).

A large-scale scenario in our study was composed of 2,061 vehicles in a 25 km by 25 km square region, including 307 intersections. The vehicular trace lasts for 20 minutes which is considered to be long enough<sup>\*1</sup>. For example, a vehicle can move for 13 km within 20 minutes with an average speed of 40 km/hr. There were approximately 100–180 vehicles that passed through the intersections selected for the stud-

ies.

## 5.2 Simulation Models

We had defined metrics based on the requirements of the ASV project. The ASV project motivated extensive discussions on many parameters based on the real information before determining such requirements. To achieve a realistic study of the IVC, we decided to follow the ASV's requirements and parameters as much as possible. The factors and parameters related to the simulation setup are detailed here.

The ns-2 simulator includes three radio propagation models: the Free Space Model, the Two-Ray Ground Reflection Model, and the probabilistic Shadowing Model<sup>6)</sup>. The free space propagation model assumes the ideal propagation condition which is far from the real implementation. The two-ray ground reflection model which is often used in performance studies of routing protocols<sup>3),5),15)</sup> considers both the direct path and a ground reflection path. It is shown<sup>16)</sup> that this model gives more accurate prediction at a long distance than the free space model. However, the free space model and the two-ray model predict the received power as a deterministic function of the distance. As a result, the communication range is represented as an ideal circle which does not reflect the complexity of real radio system according to the reports<sup>18),23)</sup>.

In practice, the received power at a given distance is a random variable due to multipath propagation effects, which are also known as fading effects. We use the shadowing model which considers these effects in our studies. Vehicles using this model can only probabilistically communicate when staying near the edge of the communication range. The protocol that assumes an ideal circle performs much poorly under such dynamic conditions. We adjusted the Shadowing model so that the probability of a successful transmission in our studies would be 70% at 200 meters. This value is determined according to the diameter of intersection zone which is set to 400 meters. In particular, some target packets need to be relayed within the intersection zone in order to distribute the information to other target vehicles.

The ASV project defines the requirements for a collision warning system. One major requirements is that a vehicle must have fresh information about the neighboring vehicles within a certain time (100 ms) to realize collision warn-

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\*1 Large-scale simulation with long simulation time requires more memory which is limited by the operating system.

ing system. Fresh information means a vehicle updates its own informations (location, speed, etc.) every 100 ms and informs target vehicles by sending a packet including such informations every 100 ms. If the vehicles cannot receive fresh information (or packets) within 100 ms, the application might fail to give a warning in time. Consequently, a vehicle needs to send a packet every 100 ms which is equal to a transmission rate of 10 packets/second. This transmission rate of 10 packets/second is one of the ASV's requirements.

However, it is very hard to achieve 100% packets reception rate due to the fading effect, the multipath propagation effect, the ground reflection, the noise and so on. Therefore, in order to increase the probability that other vehicles receive at least one packet within a given time (100 ms), one solution is to send a packet multiple times within a period of 100 ms. This solution is suggested by ITS Forum<sup>9)</sup>. The ITS Forum is an organization that determines techniques to satisfy the ASV's requirements. Therefore we used faster transmission rates than the ASV's requirement (10 packets/second or 1 packet per 100 ms) in our simulations. For example, if each packet is sent five times within 100 ms, the transmission rate will be 5 packets per 100 ms or 50 packets/second.

Each vehicle in the collision warning system sends packets periodically to notify other vehicles of its information. Even if a vehicle stops or moves slowly, it still needs to send its information continuously because nearby vehicles in other directions may be moving at high speeds. In our simulation, all vehicles broadcasted a 56-byte data packet periodically to realize the CWS. Packets are originated by the CBR (constant bit rate) traffic agent at the transmission interval of 20, 25, 33, 50, and 100 ms. The transmission interval is a period between each packet transmitted by a vehicle. For a transmission interval of 20 ms as an example, if the first packet is transmitted at 0 ms, the second packet will be transmitted at 20 ms, the third packet will be transmitted at 40 ms, and so on. In other words, transmission rate used in the simulations are 50, 40, 30.3, 20, and 10 packets/second, respectively. The transmission rate is a reciprocal function of the transmission interval. We set the transmission rate to 10, 20, 30.3, 40, and 50 packets/second in order to study the performance of protocols when sending each packet 1, 2, 3, 4, and 5 times within

100 ms, respectively. These transmission rates are much higher than the ones used in previous works<sup>3),5),14),15)</sup> which used a transmission rate of 1–8 packets/second. It is recommended to send packets with high transmission rate<sup>17)</sup> because a vehicle may be moving with a very high speed and each vehicle must notify other vehicles of its information in time. Another reason for using a high transmission rate is to study the performance of protocols when sending each packet multiple times as described above.

Each vehicle tries to disseminate messages as fast as possible in the local area around itself. Thus, we prevent the packet from being forwarded infinitely by limiting the number of hops that a packet can traverse. In our experiments, the number of hops is limited to two (i.e., TTL = 2). However, this value can be adjusted according to other parameters such as the radius of intersection zone, the communication range of vehicles, etc. The flooding protocol which is used for comparison is also set to the same TTL value so as to achieve a fair evaluation. It is intuitive that the performance of the flooding protocol decreases as the TTL increases due to the collisions of a huge number of duplicated packets. Therefore, a lower value of TTL is beneficial to the flooding protocol.

The Japan Ministry of Land, Infrastructure and Transport plans to utilize the Dedicated Short Range Communications (DSRC) technology which is already used by the Electronic Toll Collection (ETC) system to serve the IVC. Therefore, the physical layer of the communication module in our experiments used a frequency of 5.8 GHz which is currently used by the ETC system in Japan. The aim of using this frequency band is to reduce equipment costs because most vehicles in Japan are already equipped with ETC devices. Another reason is to use wireless resources (frequency) effectively. The U.S. Department of Transportation also considers DSRC for IVC<sup>8)</sup>. However, a frequency of 5.9 GHz is specifically allocated for DSRC in the U.S. The bandwidth is set to 4 Mbps as recommended in Ref. 17). We used CSMA as a MAC layer because all data packets are broadcast packets and the proposed protocol<sup>13)</sup> also specifies to use CSMA.

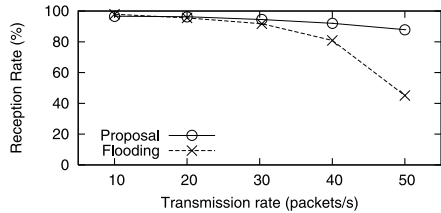
All the parameters except the packet size described in this section try to follow our IVC terminal developed for field experiments<sup>13)</sup>.

## 6. Performance Study of IVC Protocols

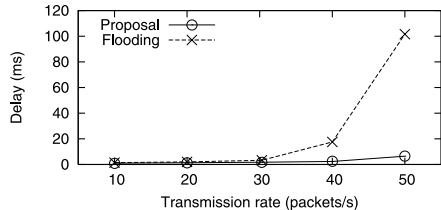
By using the above methodology and metrics, this section studies the performance of the relay control protocol<sup>13)</sup> and the flooding protocol. The performance evaluation is done at two distinct intersections separately because each intersection has different characteristics (the number of roads, the number of lanes, the existence of traffic lights, the timing and the sequence of the traffic lights, etc.) and we would like to use IVC protocols for the intersection CWS. Chosen intersections have different density of vehicles which is the number of vehicles per intersection. In particular, the density here means the number of vehicles that passed through an intersection at least once from the start to the end of the simulation which is run for 20 minutes. There are 181 and 80 vehicles that passed through the chosen intersections, i.e., the densities of vehicles are 181 and 80, respectively. Therefore, we call dense and sparse scenarios for 181 and 80 vehicles per intersection, respectively.

### 6.1 Dense Scenario

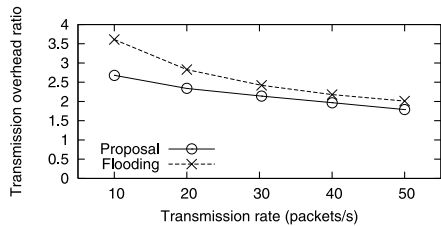
We first show the results of a scenario where the node density is high, i.e., 181 vehicles passed through the intersection in 20 minutes. Dense scenario is an unavoidable case at intersections. The conditional packets reception rate, the average end-to-end delay, and the transmission overhead ratio are shown in Fig. 5. According to Fig. 5 (a), both proposal and flooding protocol send most of the generated packets (more than 95%) to target vehicles when transmission rates are low (10 and 20 packets/second). As one would expect, the conditional packets reception rate decreases when the transmission rate increases. The proposed protocol still achieves a high reception rate (88%) at the highest transmission rate (50 packets/second). This value is higher than the requirement of 80% reception rate determined by the ASV<sup>17)</sup>. However, the reception rate of flooding protocol drops sharply until 45% at the highest transmission rate. This value is unacceptable for any applications including CWS, and is much lower than the requirement. As discussed above (Section 5.2), the ASV project requires each target vehicle to receive a fresh packet every 100 ms. To increase the probability that target vehicles receive at least one packet every 100 ms, each vehicle sends the



(a) Conditional packet reception rate.



(b) Average end-to-end delay.



(c) Transmission overhead ratio.

Fig. 5 Performance study in dense scenario.

same packet multiple times within the requirement period (100 ms). The benefit of sending a packet multiple times is explicitly lower for the flooding protocol in comparison with the proposed protocol because the reception rate of the flooding protocol (45%) is much lower than that of the proposal (88%). The results of the packet reception rate tell us that only the proposed protocol works well when sending a packet multiple times in order to realize the collision warning system. Because more than half of the packets do not arrive at target vehicles when using the flooding protocol, traffic accidents may occur due to late or lost warnings. As the transmission rate increases, the average end-to-end delays of the proposal (Fig. 5 (b)) increases from 1.4 to 6.5 ms which is much lower than the requirement of 100 ms. In contrast, the average delay of the flooding protocol increases terribly beyond 100 ms at 20-ms transmission interval.

The above results can be explained by the transmission overhead shown in Fig. 5 (c). Transmission overhead ratios of the proposal are less than the flooding protocol 0.2–0.5 which are equal to 20–50% of the originated

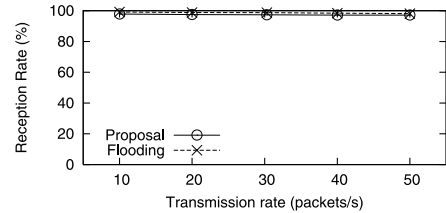
**Table 1** Number of overhead packets in a dense scenario.

Rate (packets/s)	10	20	30.3	40	50
Flooding	2,928,668	4,576,057	5,869,651	6,871,343	7,752,332
Proposal	2,173,899	3,773,274	5,200,708	6,215,117	6,937,418
Difference	754,769	802,783	668,943	656,226	814,914
%Reduction	25.77%	17.54%	11.40%	9.55%	10.51%

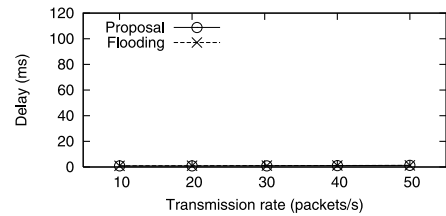
packets. We also show the exact number of overhead packets which includes both the relayed data packets and the routing packets in **Table 1**. The proposed protocol sent fewer overhead packets than did the flooding protocol for all transmission rates. The least difference between the two protocols is 656,226 packets which means the proposal decreases at least 547 packets/second for a period of 20 minutes. The proposed protocol helps reduce up to 814,914 packets or 679 packets/second in the best case. The percentages of reduction shown in the table describe the ratio of the overhead packets sent by the proposed protocol and those of the flooding protocol. The proposal reduces overhead packets for about 10% to 26% in comparison with the flooding protocol. There are fewer overhead packets as a result of the on-demand relay and the duplicate relay detection algorithm. A vehicle applying the proposed protocol relays a packet upon request while a vehicle using flooding protocol broadcasts each packet once. Although duplicate relay is possible in the proposed protocol, the DRD algorithm works well to stop unnecessary transmissions. Consequently, the proposal has a higher reception rate and a shorter end-to-end delay as shown above. The results also show that sending a packet multiple times is more beneficial to the proposal than to the flooding protocol.

## 6.2 Sparse Scenario

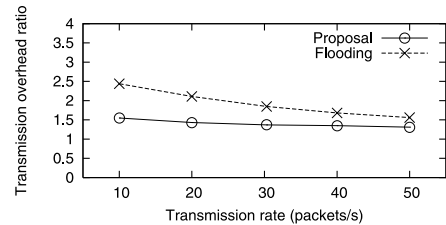
Next we study the performance of both protocols in a sparse network. In particular, there are 80 vehicles that passed through this intersection. Three performance metrics are shown in **Fig. 6**. All graphs are plotted on the same scale (X- and Y-axis) as the dense scenario (Fig. 5) for easy comparison. Conditional reception rates (Fig. 6(a)) and average end-to-end delays (Fig. 6(b)) of both protocols are approximately the same for all transmission rates. The results of both metrics are comparatively good. Reception rates are nearly 100%, and delays are around 1.0–1.3 ms which are much shorter than the requirement of 100 ms. Therefore, sending a packet multiple times is beneficial to both the proposed and the flooding protocols. However,



(a) Conditional packet reception rate.



(b) Average end-to-end delay.



(c) Transmission overhead ratio.

**Fig. 6** Performance study in sparse scenario.

the differences in transmission overhead ratios (Fig. 6(c)) are still the same as in the dense scenario, i.e., the proposed protocol has a lower transmission overhead ratio than the flooding protocol 0.2–0.7. The flooding protocol met the requirements on both the reception rate and the delay in the sparse scenario but still sent much more duplicated packets than the proposed protocol. Sending too many packets wastes wireless resources (e.g., bandwidth) which are limited.

The details of overhead packets are also summarized in **Table 2**. The number of overhead packets decreases due to fewer vehicles, while the differences of overhead packets between two protocols are approximately the same as in the case of the dense scenario. As a result, the percentages of reduction rise to 15–37%. These results are not surprising because fewer data

**Table 2** Number of overhead packets in a sparse scenario.

Rate (packets/s)	10	20	30.3	40	50
Flooding	1,485,765	2,564,392	3,393,831	4,023,616	4,591,825
Proposal	942,704	1,742,189	2,518,927	3,254,923	3,891,536
Difference	543,061	822,203	874,904	768,693	700,289
%Reduction	36.55%	32.06%	25.78%	19.10%	15.25%

packets mean fewer collisions which leads to a proper transmission of control packets. As a result, the proposed protocol can control relays and prevent duplicated relays correctly.

We conclude from the above simulations that the proposed protocol transmits data reliably and timely in a wide range of scenarios, i.e., sparse and dense scenarios. The proposed protocol is also benefit from sending the same packet multiple times in order to increase the probability that target vehicles will receive at least one packet within the period of 100 ms. It is intuitive that the vehicle density depends on places (urban area, rural area, etc.) and continuously changes with the time. Each vehicle has chances to encounter either sparse or dense scenarios. Therefore, an IVC protocol must work well in any situation to serve the intersection CWS according to ASV's requirements. In contrast, the flooding protocol failed to meet the requirements in the dense scenario. We note here that all simulation results in this section match the results of our field experiment that used real IVC terminals.

## 7. Conclusions and Future Works

This paper has carried out the performance evaluation of our previous IVC protocol developed for the intersection CWS in various scenarios. Based on the ASV's requirements, a methodology has been described to perform realistic simulations because real-world experiments on large-scale networks are very costly and may be impossible. The metrics help evaluate the performance by means of reliable and timely communications. The conditional reception rate considers only specific packets, i.e., unrelated packets are not counted even if those packets are received correctly. Therefore, we can know exactly whether protocols satisfy the requirements of the intersection CWS. The requirement on the delay is also included in the conditional reception rate in order to judge the performances of IVC protocols by using the only metric, namely, the conditional reception rate. The reception rate is also used to justify the requirement of sending the same packet

multiple times because wireless links are unreliable. Two additional metrics, i.e., the end-to-end delay and the transmission overhead, are used to explain the correctness of the conditional reception rate and the IVC protocols. The simulation results showed that the proposed protocol satisfies the requirements and suggestions determined by the ASV project and the ITS Forum. Consequently, the proposed relay control protocol is a good candidate for real implementation. We plan to extend our studies by using additional vehicular traces. The traces used in simulation will be the same as the ones used in the experiments for the ease of comparison between simulated and experimental results.

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