Proceedings of the
2007 IEEE Intelligent Vehicles Symposium
Istanbul, Turkey, June 13-15, 2007

Performance Evaluation of Protocols for Inter-Vehicle Communications

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Abstract— **Inter-vehicle communication (IVC) protocols have been studied to provide safe and comfortable driving. Each vehicle using the IVC protocols periodically broadcasts its current information (location, moving direction, speed, etc.), and other vehicles must receive such information exactly and in time. Other vehicles use received information to alert, advise, and navigate drivers, helping them become aware of the existence of other vehicles. This kind of application is helpful in various situations. For example, when a driver is approaching an intersection, the driver is not aware of vehicles that are also approaching the same intersection from another direction. To realize such inter-vehicle communication, we need to consider many issues such as protocol design, wireless standard, evaluation methodology, etc.**

Previous works on both mobile ad hoc networks and inter-vehicle communications used conventional metrics, e.g., packet delivery ratio, average delay, and path optimality, to study the performance of protocols. However, such metrics cannot be applied to inter-vehicle communications directly because the identities of the prospective receivers are a priori unknown. Moreover, many requirements must be considered to judge whether a IVC protocol satisfies the objectives of IVC applications. Although a vehicle get information properly, it is useless if that information arrives too late.

This paper proposes new performance metrics to evaluate IVC protocols by the means of *reliable and timely communications*. We also introduce a methodology to perform realistic evaluation through simulation. Realistic vehicular traces and simulation models are required to get correct evaluation results. We then use the defined metrics to evaluate the previously proposed protocol [1]. According to the simulation results, the proposed protocol is a good candidate for real implementation because it passes all requirements of inter-vehicle communications.

I. Introduction

Vehicles are going to create new services by forming spontaneous vehicular networks that transmit packets from vehicle to vehicle without the use of any deployed infrastructures. One of the promising services is a support system for safe and comfortable driving by tracking the movements of other vehicles. Vehicles transmit necessary data such as current location, moving direction, and speed for tracking purposes and the system provides appropriate alerts or navigation to drivers, helping them become aware of the existence of other vehicles that are approaching the same intersection from another direction, even if these vehicles are unseen.

The spontaneous vehicular networks are formed by inter-vehicle communications (IVCs) [2], [3], [4], [1], [5], [6]. Vehicles come across many vehicles in its driving direction and need to provide their own data promptly to other vehicles. The Carrier Sense Multiple Access (CSMA) is suitable for Media Access Control (MAC) because it allows distributed media access [3] and all data packets are broadcasted. It is also important to maintain the freshness of data because location of moving vehicles always changes along the time. This means *reliable* data deliveries are required, 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, it increases communication delay, due to considerable overhead caused by exchanging messages with a neighbor for every data transmission. Another approach is a consecutive transmission that transmits the same packet several times [3]. Even if we use this approach, in the actual environment, there are many cases where vehicles are unable to communicate with others due to the presence of obstacles and/or being outside the range of wireless transmission and so on.

Therefore, inter-vehicle communication protocols 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 traffic by relaying packets. Wireless bandwidth is a limited resource, therefore, increasing communication traffic causes large communication delays, meaning it is difficult to keep the data up to date.

Because inter-vehicle communication has peculiar requirements, we need methodology tailor-made for performance study of IVC. Intersection is our target study because drivers are unable to see vehicles approaching the same intersection from another direction due to obstacles, especially a large number of buildings in an urban area. Moreover, an intersection is a place where drivers often violate traffic regulations. It is also reported that half of the deaths (21,000 of the 43,000) annually on America's highways are caused by roadway departure and intersection related incidents [7]. Therefore, effective alert is a promising service to help drivers out of accident, and we need a metric to determine the performance of IVC protocols.

Previous works on both mobile ad hoc networks and inter-vehicle communications used conventional metrics, e.g., packet delivery ratio, average delay, and path optimality, to study the performance of protocols. However, such metrics cannot be applied to inter-vehicle communications directly because the identities of the prospective receivers are a priori unknown. Moreover, many requirements must be considered to judge whether a IVC protocol satisfies the objectives of IVC applications. Although a vehicle get information properly, it is useless if that information arrives too late. Thus we propose new performance metrics to evaluate IVC protocols.

The contributions of the paper are threefold as follows.

- **Performance Metrics**. We propose new performance metrics to evaluate information distribution of IVC protocols at an intersection. The metrics aim to study *reliable and timely communications* of IVC protocols because we must make sure that a protocol provides prompt alerts exactly.
- **Simulation Methodology**. This paper introduces methodology to perform realistic evaluations through simulations. We discuss many simulation components that highly affect performance studies. The ns-2 simulation tool [8] is used in our experiments but our methodology can be applied to any simulators.
- **Performance Study**. We study an IVC protocol through the proposed metrics by comparing with the flooding protocol. The performance studies validate the logic of protocols and can be used as a baseline to choose a protocol for real implementation.

The remainder of the paper is organized as follows. Section II discusses related work. Section III describes the overview of relay control protocol used in our evaluation. Section IV proposes performance metrics to evaluate inter-vehicle communication protocols. Section V introduces methodology to perform realistic evaluations through simulations. Section VI uses the proposed metrics to study the performance of protocols. Conclusion and Future works are presented in Sect. VII.

II. Related Work

Various kinds of performance metrics such as packet delivery ratio, average delay, path optimality, and normalized routing load have been widely used to evaluate the protocols developed for mobile ad hoc network (MANET) [9], [10], [11]. Such metrics are also used in the literature on inter-vehicle communications [2], [5], [6]. However, we cannot simply apply those classic metrics to IVC protocols because the identities of the prospective receivers are a priori unknown.

We must first define a target receiver before packet delivery ratio can be calculated correctly. Ko and Vaidya [12] proposed the idea of using geographic constraints to specify the target receivers when evaluating location-based multicast protocols. Briesemeister et al. [4] also used the same idea by defining the zone-of-relevance which covers the region behind the accident on the side of the highway where the accident happens. However, drivers also need to know surrounding information although no accident occurs. Thus, a different metric is required to evaluate distribution of necessary information from related vehicles. Moreover, they did not specify the distance of the zone-of-relevance which is an importance parameter when evaluating IVC protocols. Any protocols can use multi-hopping to extend the range of communication but extending the number of hops means a great number of redundant packets which affect the performance of protocols. Furthermore, evaluation was done on a straight road where a group of vehicles always move together in the same direction. If there is an intersection, a vehicle may change its direction and move away from others. Therefore, we propose to include components of road as many as possible in order to investigate the exact performance of IVC protocols (Sect. V).

Delay is an important metric for IVC protocols due to high moving speed of vehicles, especially the vehicles on expressway or superhighway. Instead of a simple average delay, we can calculate delay in other ways. For example, V. Naumov et al. [5] proposed to use 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 necessary packets, not all of packets. Moreover, it is useless if a packet arrives too late. Thus, the upper bound of delay should be considered in order to determine timeliness of data packets.

III. Overview of Relay Control Protocol

We briefly describe our relay control protocol [1] used in the performance study. Each vehicle is assumed to have a unique address and all vehicles periodically broadcast a packet containing location, direction, speed and so on. Packet header contains any necessary control information, i.e., an individually distinguishable source address, sequence number, and hop count. The proposed relay control protocol aims to reduce delays and probability of packet collision by reducing communication traffic. The protocol provides indirect communications for vehicular networks by relaying a packet from vehicle to vehicle. A vehicle relays received packets based on necessity. In other words, the vehicle does not relay other vehicle's packets unless required.

There are two typical cases that the request generates. First, a vehicle sends request message when the wireless quality of a neighboring vehicle deteriorates. The quality degradation can be detected from the received radio intensity and/or the packet reception rate. Second, a vehicle asks for packet relay when the vehicle meets any new vehicles. In this case, the vehicle starts to relay packets of its current neighboring vehicles to the newly met vehicles, and vice versa.

Moreover, a vehicle removes unnecessary communication traffic by avoiding duplicate relays through a duplicate relay detection (DRD) algorithm. This function avoids the possibility of the same packets being relayed by multiple vehicles. A vehicle can stop its duplicate relay and it can also inform other vehicles of their duplicate relays. Duplicate relay is determined from a packet header that contains a source address, sequence number, and hop count. In addition to the above case, the protocol can also cope with hidden terminal problem which incurs duplicate relay.

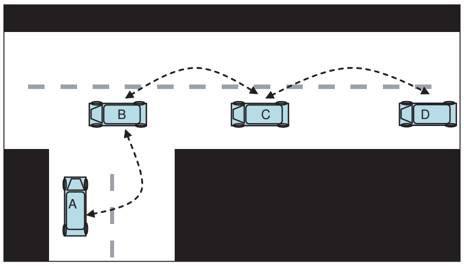

Fig. 1. The driver in vehicle D is not aware of the existence of vehicle A due to obstructions at the corner of intersection. Vehicle B and/or C can help relay A's packet to D.

Consequently, overhead transmission decreases because few extra data packets are added to a normal packet. In addition, the protocol achieves shorter communication delay because vehicles have free access to the media.

IV. Performance Metrics

Information distribution around the vicinity of intersection is important and helpful because a driver is not aware of vehicles that are approaching the same intersection from another direction if there are buildings at the corner of the intersection as shown in Fig. 1. The driver in vehicle D is not aware that vehicle A is approaching the same intersection, and vice versa. If traffic light does not exist, the accidents always occur at the intersection like this according to the report [13]. With the help of vehicle B and/or C (packet relay), the driver D can know the existence of vehicle A, and vice versa. This paper proposes *conditional reception rate* as a new metric to evaluate information distribution around an intersection. This metric is based on the requirements discussed in the Advanced Safety Vehicle (ASV) project[1] [13]. An evaluation on a straight road is less important than an intersection because a driver has longer and wider vision on a straight road. Driving automation and sensor systems also help a driver well on a straight road when comparing to an intersection.

In addition to conditional reception rate, average delay and overhead transmissions are also used to study the performance of IVC protocols.

A. Conditional Reception Rate

As discussed above, the identities of the prospective receivers are a priori unknown and highly change along the time due to high mobility of vehicles. To evaluate IVC protocol effectively, we must know the receivers, i.e., unrelated receivers must be excluded from the evaluation. Therefore, we propose to use an *intersection zone* to determine the target vehicles which are supposed to receive the packet. The intersection zone is a circular region which centers at the center of the intersection and has a radius of r meters. The radius r is set to 200 meters in our evaluation according to extensive study of the ASV project. To achieve the purpose of safety driving, the packet sent from any vehicle in the intersection zone must be received by all vehicles which stay inside the same intersection zone at the time of packet transmission. As shown in Fig. 2, six vehicles staying inside the intersection zone must get information from the others. Another requirement discussed in the ASV project is delay. Any packet from a target vehicle must arrive 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 as shown in Eq. (1).

[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.

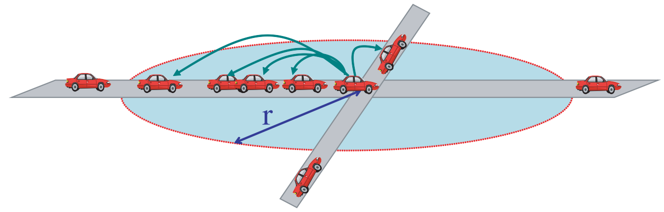

Fig. 2. Each vehicle in the intersection zone (circular region) must receive information from the others in the same intersection zone.

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

N_{z_i} is the number of vehicles staying 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 $N_{z_i} - 1$. 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).

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

The conditional reception rate in Eq. (2) is a ratio between the number of all target packets which is actually received and the number of all target packets which is supposed to be received. Note that the packet whose delay is more than the threshold (100 ms) is marked as a failed reception, although it arrives the target receiver correctly. The conditional reception rate proposed here is a useful metric to determine reliability and timeliness of IVC protocol.

B. Average End-to-End Delay

Average end-to-end delay is an important metric for studying performance of IVC protocols in details because protocols that send a large number of duplicated data packets and routing packets can also increase the probability of packet collisions and may delay data packets by queuing them in the buffer. Delay calculation is based on the same concept as conditional reception rate to achieve safety driving purpose. In particular, we consider only packets that are sent from vehicles staying inside the intersection zone. The target receivers are the vehicles staying 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 average end-to-end delay of actually received packets to determine how fast the protocol can transmit data comparing to the above requirement (100 ms). The packets that take more than 100 ms are also included in the calculation.

C. Transmission Overhead Ratio

Vehicular information is distributed through relay packets which mean 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. Vehicle density is very high at an intersection when traffic light is turned red. The probability of collision increases sharply if the number of relay nodes is high in such situation. Therefore, we count relayed packets which are duplicated packets as transmission overhead. The number of routing packets is also included in transmission overhead. To normalize the value of transmission overhead, the ratio between transmission overhead and the number of originally generated packets is calculated as transmission overhead ratio.

V. Evaluation Methodology

The following methodology is proposed as a guideline to perform realistic evaluation through simulation. In our experiments, we used the current release 2.30 (as of January, 2007) of ns-2 simulator [8], [14]. The ns-2 simulator was validated [15] and verified in a number of publications [5], [2], [9], [10], [11]. We first discuss the properties of realistic vehicular traces and describe the details of the trace used in our evaluation. We then articulate appropriate simulation models and parameters.

A. Vehicular Traces

The random waypoint model [11] which is a favorite mobility model of MANET researchers is far from actual vehicular movement. 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 [16]. As a result, 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 network depend heavily on the chosen mobility model [17]. Furthermore, Any MANET mobility models [18], [11], [19] fail for evaluating IVC protocols because they do not consider road parameters like lane configuration, traffic light, and other factors. Consequently, we prepared realistic vehicular traces separately, and then imported 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 movement like going straight along the road, our movement model includes complex maneuvers like lane changes or overtaking. It means we include possible factors in the model as many as possible. The route choice of each driver is affected by lane configurations such as a number of lanes, existence of a right turn lane, and directional regulation in each lane, and it is also affected by dynamic traffic information such as change of traffic light and surrounding vehicles. Note that there are not only intersections of two roads but also junctions of three roads or five roads in our road map. All kinds of intersections are considered to evaluate the intersection zone.

A large-scale scenario 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[2]. For example, a vehicle can move for 13 km within 20 simulated minutes although it uses an average speed of 40 km/hr. There were approximately 100–180 vehicles that passed through the intersections selected for the experiments.

B. Simulation Models

This section details the factors and parameters related to simulation setup. The ns-2 simulator includes three radio propagation models: Free Space Model, Two-ray Ground Reflection Model, and probabilistic Shadowing Model [14]. The free space propagation model assumes the ideal propagation condition which is very far from real implementation. The two-ray ground reflection model which are often used in performance studies of routing protocols [9], [10], [11] considers both the direct path and a ground reflection path. It is shown [20] 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 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 [21], [22].

In reality, the received power at certain distance is a random variable due to multipath propagation effects, which is also known as fading effects. We use shadowing model which consider these effects in our experiments. Vehicles using this model can only probabilistically communicate when staying near the edge of the communication range. The protocol that assumes ideal circle performs much poorly under such dynamic conditions. We adjust the Shadowing model so that the probability of a successful transmission is 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 are needed to relay within the intersection zone in order to distribute information to other target vehicles.

In our simulation, all vehicles broadcasted a 56-byte data packet periodically. Packets are originated by the CBR

[2]Large-scale simulation with long simulated time requires more memory which is limited by the operating system.

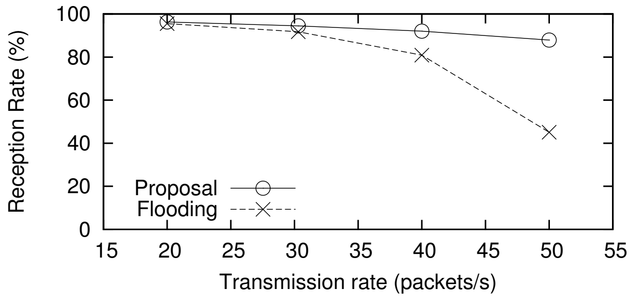

Fig. 3. Conditional packet reception rate (dense scenario).

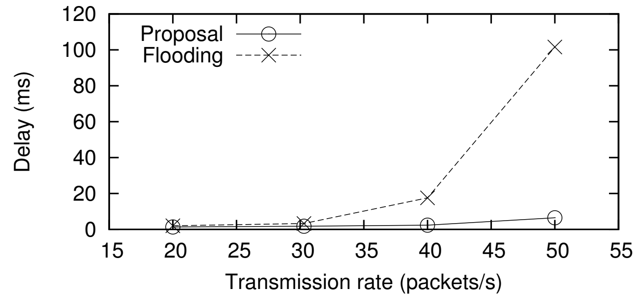

Fig. 4. Average end-to-end delay (dense scenario).

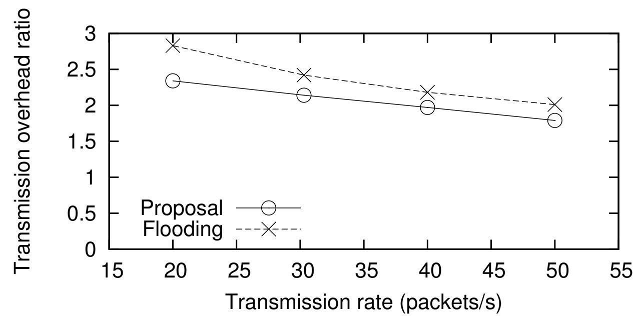

Fig. 5. Transmission overhead ratio (dense scenario).

(constant bit rate) traffic agent at the transmission interval of 20, 25, 33, and 50 ms. In other words, transmission rate used in the simulations are 50, 40, 30.3, and 20 packets/s, respectively These transmission rates are much higher than the values used in previous works [9], [10], [11], [5] which used a transmission rate of 1–8 packets/s. It is recommended to send packets with high transmission rate [13] because a vehicle may move with very high speed. Each vehicle must notify other vehicles of its information in time.

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

The Japan Ministry of Land, Infrastructure and Transport plans to utilize the Dedicated Short Range Communications (DSRC) technology used by electronic toll collection (ETC) systems to serve inter-vehicle communications. Therefore, physical layer of communication module in our experiments uses a frequency of 5.8 GHz which is currently used by ETC systems in Japan. The aim of using this frequency band is to reduce equipment cost because most of vehicles in Japan is already equipped with ETC devices. The U.S. Department of Transportation also considers DSRC for inter-vehicle communications [7]. 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 [13]. We use CSMA as a MAC layer because all data packets are broadcast packets and the proposed protocol [1] also specifies to use CSMA.

All parameters except packet size described in this section try to follow our inter-vehicle communication terminal developed for field experiments [1].

VI. Simulation Results

This section studies performance of the relay control protocol [1] and flooding protocol. We first show the results of a scenario which has high node density. Dense scenario is an unavoidable case at an intersection. Approximately 180 vehicles passed through the intersection used in this study. Conditional packet reception rate, average end-to-end delay, and transmission overhead ratio are shown in Fig. 3, 4, and 5, respectively. Conditional packet reception rate decreases when transmission rate increases as one would expect. The proposed protocol still achieves high reception rate (88%) at highest transmission rate (50 packets/s). This value is higher than the requirement of 80% reception rate determined by the ASV [13]. However, the reception rate of flooding protocol drops sharply until 45% at the highest transmission rate. This value is unacceptable for any applications and much lower than the requirement. As transmission rate increases, the average end-to-end delays of the proposal (Fig. 4) increase from 1.4 to 6.5 ms but the values are much lower than the requirement of 100 ms. In contrast, the average delays of flooding protocol increase terribly beyond 100 ms at 20-ms transmission interval.

The above results can be explained by considering transmission overhead shown in Fig. 5. Transmission overhead ratios of the proposal are less than flooding protocol 0.2–0.5, i.e., 20%–50% of the originated packets. We also show the exact number of overhead packets which includes both relayed packets and routing packets in Table I. The proposed protocol sent fewer overhead packets than flooding protocol for all of transmission rates. The least difference between the

TABLE I
NUMBER OF OVERHEAD PACKETS (DENSE SCENARIO).

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

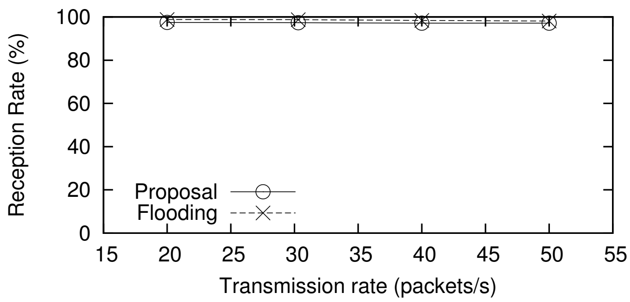

Fig. 6. Conditional packet reception rate (sparse scenario).

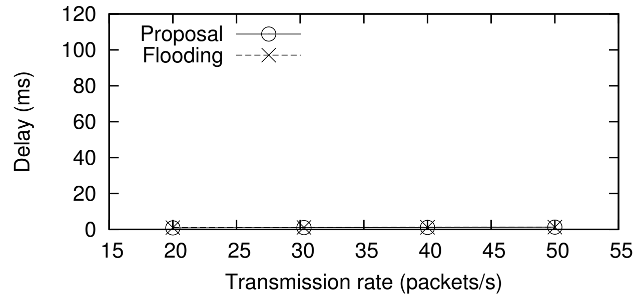

Fig. 7. Average end-to-end delay (sparse scenario).

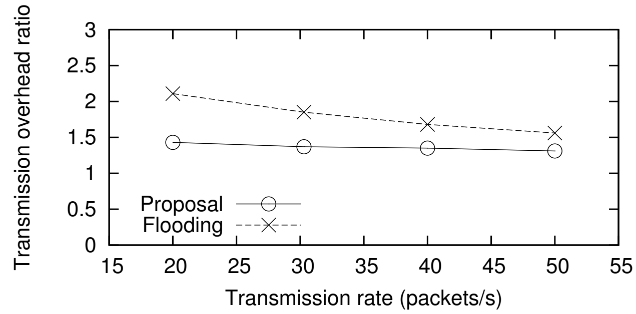

Fig. 8. Transmission overhead ratio (sparse scenario).

two protocols is 656,226 packets which mean the proposal decreases at least 547 packets/s for a period of 20 minutes. The proposed protocol helps reduce up to 802,783 packets or 669 packets/s in the best case. Percentages of reduction shown in the table describe the ratio between difference of overhead packets and overhead packets sent by flooding protocol. The proposal reduces overhead packets 10%–18% comparing to flooding protocol. Fewer overhead packets are a result of on-demand relay and duplicate relay detection algorithm. A vehicle in 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 proposal, the DRD algorithm works well to stop unnecessary transmissions. Consequently, the proposal has higher reception rate and shorter delay as shown above.

Next we study the performance of both protocols in a spare scenario comparing to the above one. There are approximately 80 vehicles that passed through this intersection. Three performance metrics are shown in Fig. 6, 7, and 8. All graphs are plotted on the same scale as the dense scenario for easy comparison. Conditional reception rate and average delay are approximately the same for all transmission rates. The results of both metrics are very well. Reception rates are nearly 100%, and delays are around 1.0–1.3 ms which are much shorter than the requirement of 100 ms. However, the differences of transmission overhead ratio are still the same as the dense scenario, i.e., the proposed protocol has lower transmission overhead ratio than flooding protocol 0.2–0.7. Flooding protocol passed both the requirements on reception rate and delay in the sparse scenario but it still sent much more duplicated packets than the proposed protocol. This means that the proposed protocol works well in various situations. The details of overhead packets are also summarized in Table II. The number of overhead packets decreases due to fewer vehicles, while the differences between two protocols are approximately same as the dense scenario. Therefore, the percentages of reduction rise to 15%–32%. These results are not surprisingly because fewer data packets mean fewer collisions which lead to proper transmission of control packets. As a result, the proposed protocol can control relay and stop duplicated relays correctly.

We conclude from the above studies that the proposed protocol transmits data reliably and timely in a wide range of scenarios. It is intuitively that vehicle density depends on places (urban area, rural area, etc.) and it varies from time to time. Therefore, an IVC protocol must works well in any situations. In contrast, flooding protocol failed to pass the requirements in dense scenarios. We note here that all simulation results in this section match the results of field experiment that uses real inter-vehicle communication terminal[3].

VII. CONCLUSION

This paper has proposed new metrics to evaluate inter-vehicle communication protocols by the means of reliable and timely communications. The proposed 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 requirement of IVC applications. Delay requirement is also included in the conditional reception rate in order to judge the performance of IVC protocols by using the only metric. Two additional metrics are used to explain the correctness of conditional reception rate and IVC protocols. The evaluation results showed that the proposed protocol

[3]Experimental results are abstained from the paper due to limited space.

TABLE II

NUMBER OF OVERHEAD PACKETS (SPARSE SCENARIO).

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

satisfies the requirements and can be a good candidate for real implementation. We plan to verify both proposed protocol and metrics by using additional vehicular traces. The traces used in simulation will be the same as ones used in the experiments for the benefit of comparison between simulated and experimental results.

ACKNOWLEDGMENTS

This work is the result of the Ubiquitous ITS project, which is supported by the National Institute of Information and Communications Technology (NICT).

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