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Packet Size-Aware Broadcasting in VANETs With Fuzzy Logic and RL-Based Parameter Adaptation

CELIMUGE WU[1], (Member, IEEE), XIANFU CHEN[2], (Member, IEEE), YUSHENG JI[3], (Member, IEEE), FUQIANG LIU[4], (Member, IEEE), SATOSHI OHZAHATA[1], (Member, IEEE), TSUTOMU YOSHINAGA[1], (Member, IEEE), AND TOSHIHIKO KATO[1], (Member, IEEE)

[1]Graduate School of Information Systems, The University of Electro-Communications, Tokyo 182-8585, Japan
[2]VTT Technical Research Centre of Finland, Oulu FI-90571, Finland
[3]Information Systems Architecture Research Division, National Institute of Informatics, Tokyo 101-8430, Japan
[4]School of Electronics and Information Engineering, Tongji University, Shanghai 200092, China

Corresponding author: C. Wu (clmg@is.uec.ac.jp)

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ABSTRACT Most existing multi-hop broadcast protocols for vehicular ad hoc networks do not consider the problem of how to adapt transmission parameters according to the network environment. Besides the propagation environment that determines the channel bit error rate, packet payload size has a significant effect on the packet loss rate. In this paper, we first discuss the effect of packet size on the packet reception ratio, and then propose a broadcast protocol that is able to specify the best relay node by taking into account the data payload size. The proposed protocol employs a fuzzy logic-based algorithm to jointly consider multiple metrics (link quality, inter-vehicle distance, and vehicle mobility) and uses a redundancy transmission approach to ensure high reliability. Since the fuzzy membership functions are tuned by using reinforcement learning, the protocol can adapt to various network scenarios. We use both real-world experiments and computer simulations to evaluate the proposed protocol.

INDEX TERMS Vehicular ad hoc networks, broadcast protocol, reinforcement learning, fuzzy logic.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) have been attracting interest for their potential roles in intelligent transport systems. An efficient multi-hop broadcast protocol is required for many VANET applications especially for the safety applications. Since there is no MAC layer acknowledgement for broadcast frames in IEEE 802.11p which is the standard to provide wireless access to vehicular networks, the problem of designing a reliable broadcast protocol is particularly challenging. There are two basic ways to provide multi-hop broadcasting in VANETs: receiver-based approach [1]–[9] and sender-based approach [10]–[15]. In the receiver-based approach, a packet forwarding decision is made at each receiver node after receiving a packet from the upstream node. In the sender-based approach, the upstream node specifies the next forwarder nodes. The sender-based approach is more efficient than the receiver-based approach in a high-density scenario which is the case of most VANETs. Beacon (hello) messages are exchanged in the sender-based approach in order to get information of vehicles in vicinity. Most existing protocols use the hello packet loss ratio to estimate the quality of a link. This estimation could be inaccurate because the size of data packets might be totally different from that of beacon messages. Several studies [16], [17] have discussed the influence of packet size on the packet reception rate and showed that shorter packets are less likely to experience collisions. However, the effect of packet size on the VANET broadcast protocols is not discussed sufficiently and is not evaluated using real-world vehicular networks.

There have been a number of sender-based broadcast protocols for VANETs. Many protocols [10]–[13] only take into account inter-vehicle distance for the relay node selection. In addition to the inter-vehicle distance, the proposal presented in [14] takes into account vehicle movements in order to provide a stable relay node. These protocols [10]–[14] intend to use the furthest node to forward broadcast data packets when other metrics are the same. This results in a high probability of packet loss at the forwarder node because the greater distance leads to weaker signal quality. Therefore, they are not suitable for real VANETs which experience channel fading. FUZZBR [15] selects relay nodes by considering multiple metrics, namely, the inter-vehicle distance, vehicle movement and signal strength. In order to improve reliability, FUZZBR retransmits a broadcast packet when the packet fails to reach the selected relay node. However, the retransmissions increase the end-to-end delay, which could be fatal when there is a strict delay constraint. Hassanabadi and Valaee [18] employ a network coding-based approach to provide high reliability in one-hop broadcast scenario. Similar to [15] and [18], most existing broadcast protocols consider the relay node selection problem and the reliability assurance (for example, retransmissions) problem separately and therefore cannot provide an efficient multi-hop broadcasting solution.

Online adaptation of transmission parameters according to the network dynamics is another important issue which is still underexplored. In our previous work, we have proposed a reinforcement learning (RL) approach to tune the parameters of fuzzy membership functions [19]. In this paper, we employ a similar approach to adjust the fuzzy membership functions using Q-learning. We first discuss the effect of packet size on the VANET broadcast protocols and then propose a multi-hop broadcast protocol which takes into account the data payload size for the relay node selection. The protocol uses different sizes of beacons messages to estimate the link quality. The proposed protocol also employs a joint relay node selection and redundancy-based approach to improve the packet forwarding probability in order to eliminate the retransmissions which could incur high delay. The inter-vehicle distance, vehicle mobility and link quality are taken into account for the relay node selection by using a fuzzy logic algorithm, and the fuzzy membership functions are tuned using a RL algorithm. We use real-world experiment and computer simulations to show the performance of the proposed protocol.

The remainder of the paper is organized as follows. In section II, we give a brief outline of related work. In Section III, we show the effect of data payload size on the broadcast packet reception ratio by using experimental data. In Section IV, we give a detailed description of the proposed protocol. Experimental results and simulation results are presented in Section V and Section VI respectively. Finally, we present our conclusions in Section VII.

II. RELATED WORK

A. RECEIVER-BASED BROADCAST PROTOCOLS FOR VANETs

Wisitpongphan et al. [1] have proposed three probabilistic and timer-based broadcast protocols: weighted p-persistence, slotted 1-persistence, and slotted p-persistence schemes. The inter-vehicle distance is considered as the main criterion for making a decision (whether forward or not). Suriyapaiboonwattana *et al.* [2] and Slavik and Mahgoub [3] discuss about adaptive setting of the forwarding probability. Mylonas et al. [4] have proposed a protocol which adaptively regulates the rebroadcast probabilities based on the vehicle velocities. Yoo and Kim [5] have proposed ROFF, a robust and fast forwarding protocol. ROFF allows each node to decide its waiting time according to a forwarding priority (an integer value) which is defined based on the empty space distribution (ESD) within the forwarding area. The overhead of ROFF is large in a high-density network because ESD information is piggybacked on the broadcast data. Wu et al. [6] have proposed DAYcast, a dynamic transmission delay based broadcast protocol for VANETs. Different from traditional receiver-based protocols, DAYcast only allows the effective neighbors (which are chosen based on position information) of a source vehicle to broadcast a received data packet. Each effective neighbor waits for a certain period of time before broadcasting a received packet. Therefore, DAYcast can be seen as a hybrid protocol which combines the receiver-based approach and the sender-based approach. Al-Kubati et al. [7] have proposed RTBP, a road topology based broadcast protocol. RTBP employs a contention-based forwarding scheme that improves broadcast performance in urban environments by exploiting available road map information. RTBP assigns the highest forwarding priority to the vehicle which has the greatest capability to send the packet in multiple directions. Sanguesa et al. [8] have proposed a real-time adaptive dissemination system that allows each vehicle to automatically adopt the most suitable dissemination scheme in order to satisfy different requirements for different scenarios. Voicu et al. [9] have proposed an approach where a forwarder node is selected by considering the signal-to-noise ratio (SNR) as well as the Euclidean distance from the sender. A rebroadcasted message by the forwarder node acts as an acknowledgment back to the previous sender. A third-party explicit acknowledgment approach (a node in the vicinity of both the source node and the forwarder node sends an acknowledgment to the source node on behalf of the forwarder node) is also proposed in [9]. However, multiple nodes could send explicit acknowledgments at the same time, and the overhead of the ACK messages is not seriously discussed.

B. SENDER-BASED BROADCAST PROTOCOLS FOR VANET

Sahoo et al. [10] have proposed a protocol in which each sender node employs a binary partition approach to delegate the forwarding duty to the furthest vehicle. Suthaputchakun et al. [11] have proposed the trinary partitioned black-burst-based broadcast protocol. Fogue et al. [12] have proposed the profile-driven adaptive warning dissemination scheme (PAWDS) which selects the most suitable forwarding node by taking into account the characteristics of the street area and the density of vehicles in the target scenario. Javed et al. [13] have proposed a multi-hop broadcast protocol which assigns the responsibility of message forwarding to only a subset of vehicles on the road, and employs explicit ACK messages to ensure reliability. The forwarder nodes are selected by taking into account the inter-vehicle distance. FUZZBR [15] specifies the relay nodes by taking into account the inter-vehicle distance, vehicle mobility and signal strength. However, none of these protocols takes into account the effect of packet payload size on the protocol performance.

C. RELIABILITY ASSURANCE METHODS FOR VANET BROADCAST PROTOCOLS

In order to provide high reliability, most existing protocols use the retransmission-based approach where each sender node retransmits a packet when the node fails to receive the corresponding acknowledgment in a predefined time period. There are two main methods to detect a packet loss, specifically, the implicit acknowledgment approach and the explicit acknowledgment approach. FUZZBR [15] employs an explicit approach where rebroadcast of a packet at the forwarder node is used as an acknowledgment to the upstream node. Javed *et al.* [13] employ explicit ACK messages to ensure reliability. The explicit acknowledgment approach has higher overhead as compared with the implicit acknowledgment approach. Voicu *et al.* [9] employ both the implicit and the explicit acknowledgment approaches. The common problem for the retransmission approach is that a high delay could occur when a packet loss happens because the retransmission time interval cannot be set to a very small value due to the risk of redundant retransmissions.

Hassanabadi and Valaee [18] have proposed an approach that improves the reliability of periodic broadcasting in VANETs. The random linear network coding is used to provide reliability for small safety messages with low overhead. However, the multi-hop broadcast problem is not discussed in [18]. In this paper, we discuss the problem of how to use network coding to improve the reliability in a multi-hop communication scenario.

III. EFFECT OF PAYLOAD SIZE: EXPERIMENTAL DATA

Figure 1 shows the effect of data payload size on the broadcast packet reception ratio. The data are acquired from real-world vehicular networks with IEEE 802.11b/g/n wireless radio (5 dBi antenna gain, and 20 dBm transmission power).[1] In addition to transmission distance which directly affects the SNR at the receiver, the payload size is another important factor which affects the probe packet reception ratio significantly. The packet reception ratio drops significantly with the increase of payload (packet) size. This shows that the conventional use of hello packet reception ratio as the indicator of link status information could be dangerous when the packet size is not considered in the estimation (which is the case of most existing broadcast protocols).

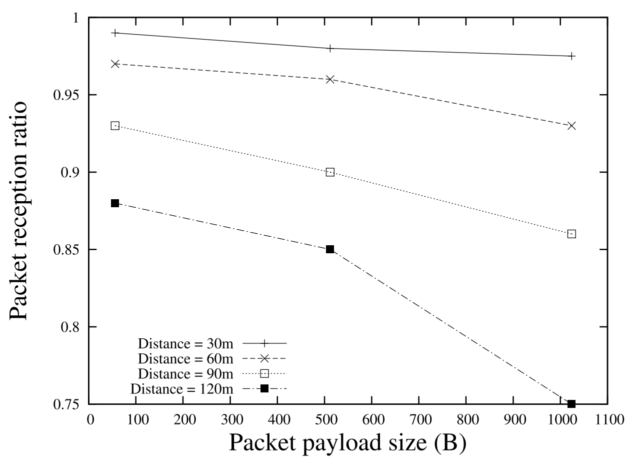

FIGURE 1. Packet reception ratio of broadcast packets for different distances and payload sizes.

IV. PROPOSED PROTOCOL

A. PROTOCOL OVERVIEW

The contribution of the proposed protocol is threefold. Firstly, the protocol employs an accurate packet forwarding probability estimation approach by taking into account the beacon size. Secondly, the protocol uses a fuzzy logic-based approach to select relay nodes, and uses a RL approach to adjust the fuzzy membership functions. Thirdly, the protocol introduces an adaptive redundancy-based approach which is used to improve the packet forwarding probability. The protocol employs a heuristic approach to conduct joint optimization of relay node selection and redundancy level selection in order to improve the overall performance.

The protocol employs a sender-based approach, and selects the best combination of relay node and redundancy level from the relay node candidates. The relay node candidates are determined by using the concept of ''Broadcast Zone'' which was first proposed in [15].

B. USING DIFFERENT SIZES OF HELLO MESSAGES TO ESTIMATE THE LINK QUALITY

We define three different sizes of hello packets, and each node randomly selects a payload size from {56, 512, 1024} (bytes) for hello messages.[2] This selection lasts for 100 seconds. If the selected payload size is not sufficient to transmit all the data required, the node uses multiple packets to transmit. If the selected size is larger than the size required, the node uses zero padding. Link quality information is maintained for each possible hello payload size ({56, 512, 1024}) (bytes). Upon reception of hello message, each node updates the link quality information for the corresponding payload size. The format of link quality information is shown in Table 1. ''$\hat{D}$'' is calculated as $\lfloor d \rfloor \bmod 10$, where d is the distance between the hello sender and receiver node, and $\lfloor \cdot \rfloor$ is the floor function. ''TS'' is the timestamp which shows the last updated time for the corresponding data. ''AVG. PRR'' shows the average value of packet reception ratio which is maintained for each $\hat{D}$. The average value is used to determine the appropriate inter-vehicle distance for relay node selection.

[1]Note that IEEE 802.11p is the standard to provide wireless access for vehicular networks. Since this paper focuses on the network layer issues, we believe that the experiments in IEEE 802.11b/g/n are sufficient to show the problem and evaluate the proposed protocol.

[2]For simplicity, we explain the protocol for the case of using three different sizes only; however, the protocol can be easily extended to support various payload sizes.

TABLE 1. Link quality information format (each node maintains an entry like this for each possible payload size).

$\hat{D}$	AVG. PRR	TS	{NbID, PRR, TS}, {NbID, PRR, TS}, ...

Each node also maintains a "PRR" and "TS" for each neighbor ("NbID" denotes neighbor ID).

C. PACKET SIZE-AWARE BROADCAST

Before broadcasting a data packet, the sender node checks the payload size, and selects relay nodes according to the corresponding beacon reception ratio. For example, if the payload size is 1024 bytes, the protocol gets the beacon reception ratio for this payload size by retrieving the corresponding link quality information. Since the beacon reception ratio acquired is more accurate, the proposed protocol can attain higher reliability and efficiency than the conventional approach.

D. TWO REDUNDANCY APPROACHES

Since there is no acknowledgment for a broadcast MAC frame, typically, retransmissions are conducted at a higher layer when a packet loss occurs. However, the retransmissions incur high delay because the retransmission interval cannot be set to too small in order to avoid unnecessary retransmissions. Hereby, we reduce the number of retransmissions by providing a higher reliability with redundancy. As shown in Fig. 2, the proposed protocol introduces two redundancy approaches: pure redundant transmission and network coding-based redundant transmission. In the pure redundant transmission, a packet is transmitted multiple times consecutively. In the network coding-based redundancy transmission, the packet is encoded before transmission in order to reduce the number of transmissions.

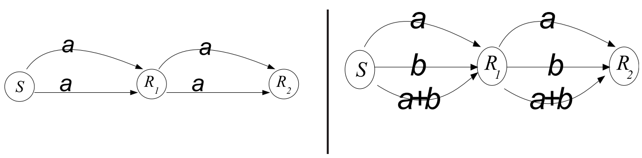

FIGURE 2. Redundant transmissions (left: pure redundancy, right: network coding-based redundancy).

In case of using the network coding-based approach, we encode packets based on a batch of m packets where m is set to 2 by default. The sender can construct a batch of linearly coded packets $Y = CX$ as

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_{m+n} \end{pmatrix} = \begin{pmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,m} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m+n,1} & c_{m+n,2} & \cdots & c_{m+n,m} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix}, \quad (1)$$

where n is the number of redundant packets. The receiver can retrieve the original packets if the node can receive m packets (regardless of whether they are the original or encoded). If we use n redundant packets for each batch of packets (m packets), the batch reception probability is

$$\begin{aligned}
P_{(1,p_l,1)} &= 1 - p_l^2; \\
P_{(1,p_l,2)} &= 1 - p_l^3; \\
&\cdots \quad \cdots \\
P_{(1,p_l,n)} &= 1 - p_l^{(n+1)}; \\
P_{(2,p_l,1)} &= 1 - p_l^3 - \binom{3}{2} p_l^2 (1-p_l); \\
P_{(2,p_l,2)} &= 1 - p_l^4 - \binom{4}{3} p_l^3 (1-p_l); \\
&\cdots \quad \cdots \\
P_{(2,p_l,n)} &= 1 - p_l^{(n+2)} - \binom{n+2}{n+1} p_l^{n+1} (1-p_l); \\
P_{(3,p_l,1)} &= 1 - p_l^4 - \binom{4}{3} p_l^3 (1-p_l) - \binom{4}{2} p_l^2 (1-p_l)^2; \\
P_{(3,p_l,2)} &= 1 - p_l^5 - \binom{5}{4} p_l^4 (1-p_l) - \binom{5}{3} p_l^3 (1-p_l)^2; \\
&\cdots \quad \cdots \\
P_{(3,p_l,n)} &= 1 - p_l^{(n+3)} - \binom{n+3}{n+2} p_l^{(n+2)} (1-p_l) \\
&\quad - \binom{n+3}{n+1} p_l^{(n+1)} (1-p_l)^2; \\
P_{(m,p_l,n)} &= 1 - \sum_{i=0}^{m-1} \binom{m+n}{m+n-i} p_l^{(m+n-i)} (1-p_l)^i, \quad (2)
\end{aligned}$$

where p_l is the packet loss rate. Based on (2), the protocol calculates the packet forwarding ratio for each possible relay node and redundancy level, and then chooses the best combination.

E. JOINT RELAY AND REDUNDANCY SELECTION

The relay node selection and redundancy level selection are jointly considered in the proposed protocol. The relay nodes are selected by taking into account the redundancy gain. More specifically, we can reduce the number of transmissions by adding redundancy to data packets and selecting larger-distance relay nodes. In contrast, when there is no choice for the relay node selection, the redundancy level is tuned according to the link quality of the relay node selected. The problem of joint relay and redundancy selection can be defined as

$$\begin{aligned}
&\underset{d,m,n}{\text{minimize}}\ N = \frac{1}{d} \cdot \frac{n+m}{m} \cdot \frac{1}{f_P(d,m,n)} \\
&\text{subject to } f_P(d,m,n) > PFR_C, \quad (3)
\end{aligned}$$

where N is the number of required transmissions for a data packet. m is the number of packets in a batch processing, and n is the number of redundant packets for the batch processing. $f_P(d, m, n)$ is the packet forwarding probability which is determined by the inter-vehicle distance (d), and the redundancy level ($\frac{n+m}{m}$). PFR_C is the packet forwarding probability constraint. The objective is to minimize the number of required transmissions while satisfying the packet forwarding probability constraint. The longer-distance relay could reduce the number of transmissions for the multi-hop broadcast ($\frac{1}{d}$ in the equation). However, with the increase of inter-vehicle distance, the packet forwarding probability [$\frac{1}{f_P(d,m,n)}$ in the equation] drops, resulting in retransmissions.

We use a heuristic algorithm to solve the problem. We take into account three metrics, specifically, link quality, inter-vehicle distance and vehicle mobility, for the relay node selection. The relay node selection consists of two steps. In the first step, we use a fuzzy logic-based algorithm to rank all the possible relay node candidates. The fuzzy logic algorithm can provide fast and efficient ranking by taking into account multiple metrics. In the second step, we compare the top ten[3] candidates, and choose the best combination of relay node and redundancy.

1) FIRST STEP – FUZZY LOGIC-BASED RELAY NODE EVALUATION

We take into account three metrics for the evaluation specifically mobility metric (MM), distance metric (DM), and link quality metric (LM) (calculated as described in §IV-B). Mobility metric (MM) is calculated as

$$MM(X) \leftarrow (1-\alpha)\times MM(X)+\alpha\times(1-\frac{|d_i(X)-d_{i-1}(X)|}{R}), \quad (4)$$

where MM indicates the mobility level of the neighbor node. The higher the MM value, the more stable the neighbor node is. $d_i(X)$ is the distance between the current node and the neighbor node at time i. We set α to 0.7 according to our experimental results. This parameter reflects how quickly the averaged value changes with network topology. If the value is too large, the estimation could be affected by an immediate misleading value which does not show long-term mobility. MM is initialized to 0. DM is calculated as

$$DM(X)=\begin{cases}\frac{d(X)}{R}, & d(X)<=R;\\ 1, & d(X)>R,\end{cases} \quad (5)$$

where R is the reference transmission range. R is set based on the type of transceivers. Considering the transceivers used in our experiment (see Fig. 1), we set R to 120 m in this paper.

[3]This number could be tuned based on the application requirement.

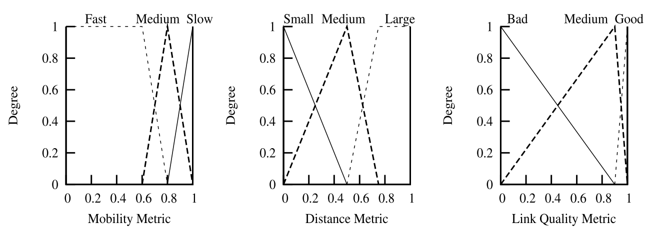

FIGURE 3. Fuzzy membership functions (Left: MM, Middle: DM, Right: LM).

TABLE 2. Rule base.

	Mobility	Distance	Link quality	Rank
Rule1	Slow	Large	Good	Perfect
Rule2	Slow	Large	Medium	Good
Rule3	Slow	Large	Bad	Unpreferable
Rule4	Slow	Medium	Good	Good
Rule5	Slow	Medium	Medium	Acceptable
Rule6	Slow	Medium	Bad	Bad
Rule7	Slow	Small	Good	Unpreferable
Rule8	Slow	Small	Medium	Bad
Rule9	Slow	Small	Bad	VeryBad
Rule10	Medium	Large	Good	Good
Rule11	Medium	Large	Medium	Acceptable
Rule12	Medium	Large	Bad	Bad
Rule13	Medium	Medium	Good	Acceptable
Rule14	Medium	Medium	Medium	Unpreferable
Rule15	Medium	Medium	Bad	Bad
Rule16	Medium	Small	Good	Bad
Rule17	Medium	Small	Medium	Bad
Rule18	Medium	Small	Bad	VeryBad
Rule19	Fast	Large	Good	Unpreferable
Rule20	Fast	Large	Medium	Bad
Rule21	Fast	Large	Bad	VeryBad
Rule22	Fast	Medium	Good	Bad
Rule23	Fast	Medium	Medium	Bad
Rule24	Fast	Medium	Bad	VeryBad
Rule25	Fast	Small	Good	Bad
Rule26	Fast	Small	Medium	VeryBad
Rule27	Fast	Small	Bad	VeryBad

The membership functions and fuzzy rules are defined as in Fig. 3 and Table 2, respectively. The membership functions for the distance metric and the link quality metric are defined according to our experimental data (see Fig. 1). Based on the output member function defined in Fig. 4, Center of Gravity (COG) method is used to defuzzify the fuzzy result. Since the fuzzy logic can reconcile conflicting objectives, this step can provide a quick ranking of multiple candidates (the neighbor vehicles).

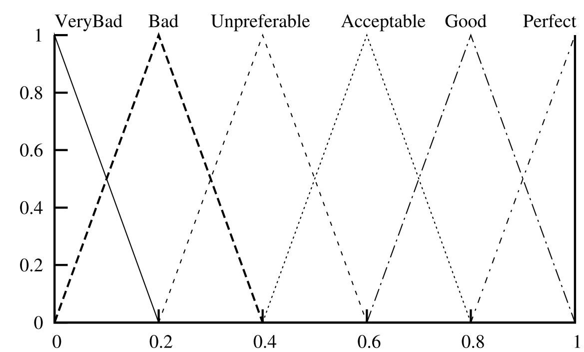

FIGURE 4. Output membership function.

2) SECOND STEP – JOINT SELECTION OF RELAY NODE AND REDUNDANCY LEVEL

As shown in Algorithm 1, we first select the top ten relay node candidates according to the ranking conducted previously. After that we choose the best combination of relay node and the corresponding redundancy level. If there are multiple packets waiting for transmission, the proposed protocol employs network coding to encode the packets before transmissions. Here, considering processing complexity, we set m to 2.

Algorithm 1 Joint Selection of Relay Node and Redundancy Level

```
Select the top ten candidates for the relay node selection
    according to the ranking conducted by the fuzzy logic-
    based evaluation.
if (There are multiple packets waiting for transmission in
    the send queue) then
    Use two packets (m = 2) as a batch.
    Choose the network coding-based redundancy
        approach.
else
    Choose the pure redundancy approach.
end if
Find the best combination of relay node and redundancy
    level according to (2) and (3).
```

Algorithm 2 Update of Q-Table

```
Execute action x at state s, and transmit a data packet.
if (The packet is successfully delivered) then
    Update Q-value [Q(s, x)] with a positive reward
        [see (6)].
    Select the next action [choose the action with the high-
        est Q-value with probability 1 − p, and do exploration
        (Algorithm 4) with probability p].
else
    Update Q-value [Q(s, x)] with zero reward and
        max_y Q(s_{t+1}, y) [see (6)].
    Select the next action [choose the action with the high-
        est Q-value with probability 1 − p, and do exploration
        (Algorithm 3) with probability p].
end if
```

F. Q-LEARNING BASED PARAMETER ADAPTATION

1) Q-LEARNING MODEL

We use a RL algorithm, specifically Q-learning, to tune the fuzzy membership functions in order to handle various network situations autonomously. The Q-learning model is defined as follows. The entire network is the environment. Each node (vehicle) in the network is an agent. Each combination of the three fuzzy membership functions is a state of the agent. The set of all possible combinations of fuzzy membership functions is the state space. The learning task is to find the best parameter(s) for the corresponding network environment in relation to the feedback (this will be explained in §IV-F.3). The possible actions are: **1) to increase the weight of DM, 2) to reduce the weight of DM, 3) to increase the weight of MM, 4) to reduce the weight of MM, 5) to increase the weight of LM, 6) to reduce the weight of LM, and 7) to use current settings.**

2) UPDATE OF Q-VALUES

Each agent makes an exploratory move with probability p (exploration), and chooses the action with the highest Q-value with probability $1 - p$ (exploitation). The probability p is calculated by $1 - Q_{max}$ where Q_{max} is the Q-value of the best action.

Each agent updates its Q-table after sending a data packet. If the data packet is received by the next forwarder (relay) node in the predefined time period (40 ms by default), the agent (sender node) gets a positive reward. If the data packet is lost, the agent gets zero reward (see Algorithm 2). Q-table is updated as

$$Q(s_t, x) \leftarrow \alpha \times \left\{R + \gamma \times (1 - R) \times \max_y Q(s_{t+1}, y)\right\} + (1 - \alpha) \times Q(s_t, x). \quad (6)$$

The learning rate α is set to 0.7. Since the data transmissions happen frequently, such a value is enough to reflect the network topology changes. The discount factor γ is set to 0.9. The reward is calculated as

$$R = \begin{cases} 1, & \text{if the packet is received;} \\ 0, & \text{if the packet is lost.} \end{cases} \quad (7)$$

3) EXPLORATION POLICY

The actions (exploration) conducted by an agent are dependent on the reception status of the previously sent packet. The sender node judges a packet as delivered when the node detects rebroadcast of the packet from the selected relay node. A packet loss can occur at the selected relay node due to the following reasons: (1) the weight of the LM is too small, which results in that the relay node experiences weak link quality; (2) the weight of the DM is too large which results in that the relay node is determined by the distance only; or (3) the weight of the MM is too large, which results in that the relay node is determined by the mobility only. The corresponding actions should be: (1) to increase the weight of LM, (2) to reduce the weight of DM, or (3) to reduce the weight of MM. However, we have to decide which the dominant factor is. We first compare between $\frac{LM_{relay}}{LM_{second}}$, $\frac{DM_{relay}}{DM_{second}}$, and $\frac{MM_{relay}}{MM_{second}}$ to find the largest one. Here, LM_{relay} is the LM value of the selected relay node, and LM_{second} is the LM value of the relay candidate which has the second largest value. If $\frac{LM_{relay}}{LM_{second}}$ is the largest one, we increase the weight of MM because the packet may be lost due to movement of the relay node. If $\frac{DM_{relay}}{DM_{second}}$ (or $\frac{MM_{relay}}{MM_{second}}$) is the largest, we reduce the weight of DM (or MM).

Algorithm 3 shows the actions triggered when the packet is lost. When the dominant factor is LM, the packet loss could be due to the relay node movement. Therefore, we have to increase the weight of MM (the dominant reasons incur packet loss could be weak signal strength or vehicle mobility). If DM is the dominant factor, we have to reduce the weight of DM, and increase the weight of LM in order to improve the packet reception probability at the relay node. Similarly, we have to reduce the weight of MM value,

Algorithm 3 Actions at Each Sender Node When a Packet Is Lost

Find the dominant factor used for the relay node selection.
switch (the dominant factor)
case LM**:**
  Increase the weight of MM.
case DM**:**
  Reduce the weight of DM, and increase the weight of LM.
case MM**:**
  Reduce the weight of MM value, and increase the weight of LM.
end switch

and increase the weight of LM when the dominant factor is MM.

Algorithm 4 shows the actions triggered when the packet is delivered. When the dominant factor is LM, the relay node selection algorithm could overweight LM. Therefore, the best response is to reduce the weight of LM, which increases the weight of other two factors indirectly. If the dominant factor is DM, the current setting is efficient because it allocates the highest weight to the distance factor. If the dominant factor is MM, we have to reduce the weight of MM in order to improve the efficiency of the algorithm (this increases the weight of DM relatively).

Algorithm 4 Actions at Each Sender Node When a Packet Is Delivered

Find the dominant factor used for the relay node selection.
switch (the dominant factor)
case LM**:**
  Reduce the weight of LM.
case DM**:**
  Use current settings.
case MM**:**
  Reduce the weight of MM.
end switch

4) DISCRETIZING STATE AND ACTION SPACES

State space S is defined as $S = \{S_{DM}, S_{MM}, S_{LM}\}$ where S_{DM}, S_{MM}, and S_{LM} denote the corresponding state spaces for DM, MM, and LM respectively. Action space is defined as $A = \{A_{DM}, A_{MM}, A_{LM}\}$ where A_{DM}, A_{MM}, and A_{LM} are the corresponding action spaces for DM, MM and LM, respectively.

We use S_{DM} as an example to show how to discretize state space for fuzzy membership functions. Each state of DM membership function is expressed as $(SM_1, SM_2, SM_3), (MD_1, MD_2, MD_3), (LA_1, LA_2, LA_3)$ where SM, MD, and LA denote the linguistic variable {Small}, {Medium}, and {Large} respectively. As shown in Fig. 5, since the membership functions are triangle (or trapezoid but one parameter is fixed), we only need to tune three parameters for each linguistic variable (nine parameters in total for DM). For example, for the linguistic variable {Small}, the three parameters are SM_1, SM_2, and SM_3. What we need to configure for each parameter is only the value of x-axis (the value of y-axis is fixed for each point).

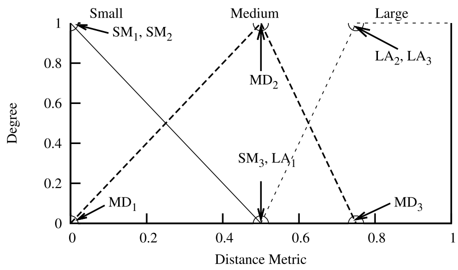

FIGURE 5. Example of state space for DM.

In order to reduce the size of Q-table which is determined by action space, we reduce the number of tunable parameters to three (SM_2, MD_2 and LA_2) by using the following constraints: (1) $SM_2 \equiv MD_1$; (2) $MD_2 \equiv SM_3 \equiv LD_1$; (3) $MD_3 \equiv LA_2$; and (4) SM_1 and LA_3 are static, where $\equiv$ denotes the two parameters are equivalent (the values of x-axis are the same). Similarly, we define three tunable parameters for MM and LM, respectively. Now we have nine tunable parameters for fuzzy membership functions. We use P_{DM1}, P_{DM2}, P_{DM3}, P_{MM1}, P_{MM2}, P_{MM3}, P_{LM1}, P_{LM2}, P_{LM3} to denote these parameters, where P_{DM1} is the first tunable point (the value for x-axis) for DM. Possible values for each parameter are selected from {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1}. The number of possible states is 11^9, which is a very large number. Therefore, we only store the parameters for the linguistic variable {Medium} (P_{DM2}, P_{MM2} and P_{LM2}) in the Q-table. Other parameters can be calculated according to the initial membership function as shown in Fig. 6. Here, we defined two rules to control other two parameters: (1) if the action is "to reduce the weight of DM" [reduce P_{DM2}, see Fig. 6 (middle)], then P_{DM1} does not change, and P_{DM3} changes while keeping the difference between P_{DM3} and P_{DM2} unchanged; (2) if the action is "to increase the weight of DM" [increase P_{DM2}, see Fig. 6 (right)], then P_{DM3} does not change, and P_{DM1} changes while keeping the difference between P_{DM1} and P_{DM2} constant. In this way, a state is defined as $s = \{P_{DM2}, P_{MM2}, P_{LM2}\}$.

V. EXPERIMENTAL RESULTS

We used a real-world VANET to evaluate the performance of the proposed protocol. The proposed protocol was implemented in Ubuntu 12.04 LTS. We used 10 cars to generate the VANET. Each car was equipped with a laptop computer and an USB wireless adapter (5dBi antenna gain and 20 dBm transmission power) as shown in Fig. 7. The wireless adapters

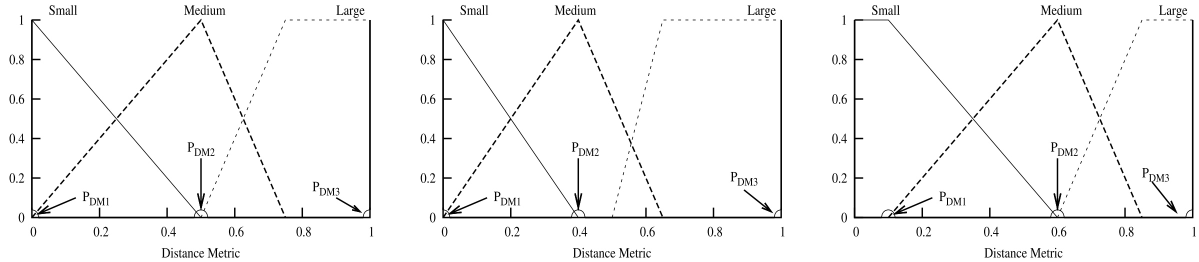

FIGURE 6. Example of tuning DM membership functions (left: before tuning, middle: after reducing the weight of DM, right: after increasing the weight of DM).

FIGURE 7. Experimental devices.

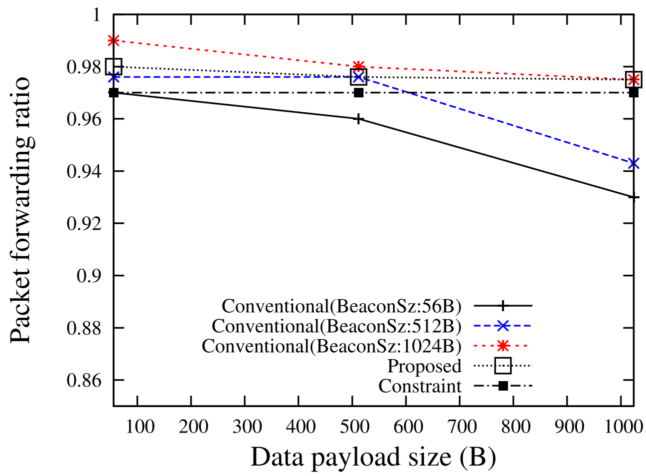

FIGURE 8. Packet forwarding ratio for different sizes of data packets.

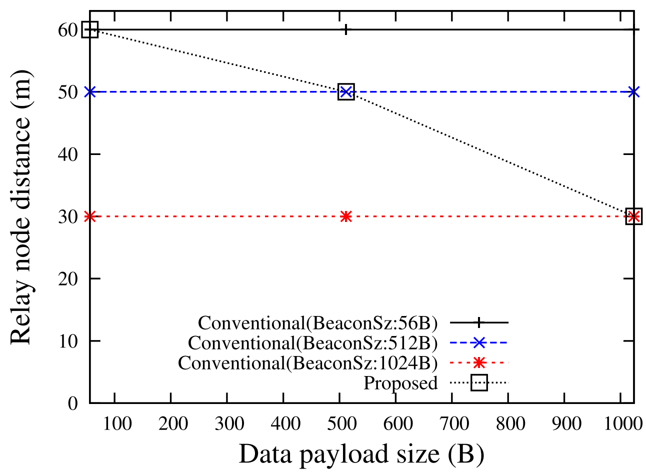

FIGURE 9. Relay node distance for different sizes of data packets.

ran in ad-hoc mode and communicated with each other using 2.4GHz IEEE 802.11b/g/n wireless radio. We used two-lane one-way straight road to evaluate the proposed protocol. The maximum allowable velocity was 60 km/h. The minimum distance between two neighbor vehicles was 10m (when two vehicles belong to the same lane, the minimum inter-vehicle distance was 20 m, and when they belong to different lanes, the minimum distance was 10 m).

The proposed protocol was compared with the conventional approach with different beacon sizes. In order to clearly show the effects of beacon size consideration and adaptive redundancy, in this paper, ''Proposed'' denotes the proposed protocol without redundancy, and ''Proposed with redundancy'' shows the proposed protocol with redundancy. ''Conventional(BeaconSz:56B)'' denotes the conventional approach with beacon size of 56 bytes.

Figure 8 shows the packet forwarding ratio for different sizes of data packets. In the figure, ''Constraint'' denotes the packet forwarding probability constraint [PFR_C in (3)]. When the beacon size is smaller than the data payload size, the conventional approach cannot satisfy the packet forwarding constraint. This is because the conventional approach overestimates the link quality. When the beacon size is larger than the data packet size, the conventional approach is able to provide high reliability. However, as we can see from Fig. 9, the multi-hop broadcasting is inefficient because the relay node distance is too small (due to the underestimation of the link quality). Since the proposed protocol takes into account the beacon size for the relay node selection, the proposed protocol can attain a high packet forwarding radio while providing an efficient relaying.

VI. SIMULATION RESULTS FOR LARGE-SCALE VEHICULAR NETWORKS

We used ns-2.34 [20] to conduct simulations in straight road scenarios by generating vehicle movement with [21]. We used a straight road which had two lanes in each direction. All lanes of the road were 2000 m in length. The maximum allowable vehicle velocity was 100 km/h. Wireless channel parameters were set based on our measurement (see Fig. 1). We evaluated the proposed protocol for different numbers of nodes. In the following figures, "Conventional(BeaconSz:56B, PLSz:56B)" denotes the performance of the conventional approach when both the beacon size and payload size are 56 bytes.

A. PACKET FORWARDING RATIO

Figs. 10, 11 and 12 show the packet forwarding ratio for different numbers of nodes with payload size of 56 bytes, 512 bytes and 1024 bytes, respectively. The proposed protocol can attain a very high packet forwarding ratio for various sizes of data packets. When the redundancy is used, the proposed protocol ("Proposed with redundancy") can provide almost 100 percent packet forwarding ratio. The performance of the conventional approach is dependent on the size of beacon packets. If the beacon size is smaller than the data packet size, the conventional approach results in low packet forwarding ratio. In contrast, when the beacon size is larger, the conventional approach fails to choose a relay node which can provide large dissemination progress. This results in a larger number of hops (longer dissemination path) for multi-hop dissemination.

In Fig. 12, we observe a slight drop of packet forwarding ratio when the node density changes from 100 to 150. The reason is that when the number of nodes is 100, the proposed protocol uses a very near node (the protocol uses a node located in distance smaller than 30 m because the protocol has to satisfy the packet forwarding ratio constraint and there are no better nodes) to forwards packets, and with the increase of node density the protocol becomes able to use more efficient nodes (30 m or little bit more) as the relay nodes. This results in a little drop of packet forwarding ratio but increases the efficiency of the proposed protocol in term of the number of transmissions. The proposed protocol can provide a good performance as far as the network density is sufficiently high.

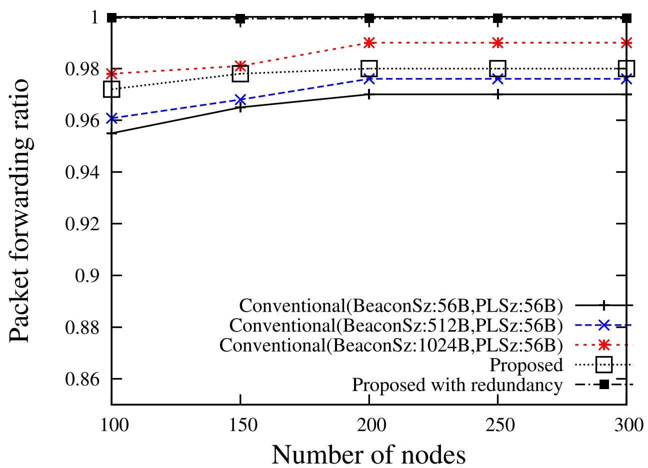

FIGURE 10. **Packet forwarding ratio for various numbers of nodes (payload size = 56 bytes).**

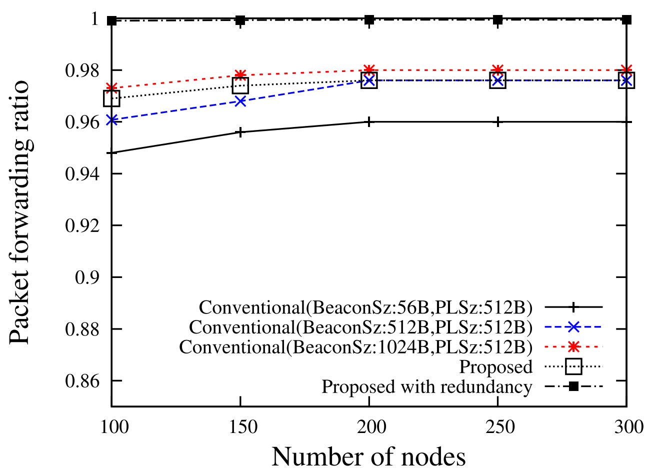

FIGURE 11. **Packet forwarding ratio for various numbers of nodes (payload size = 512 bytes).**

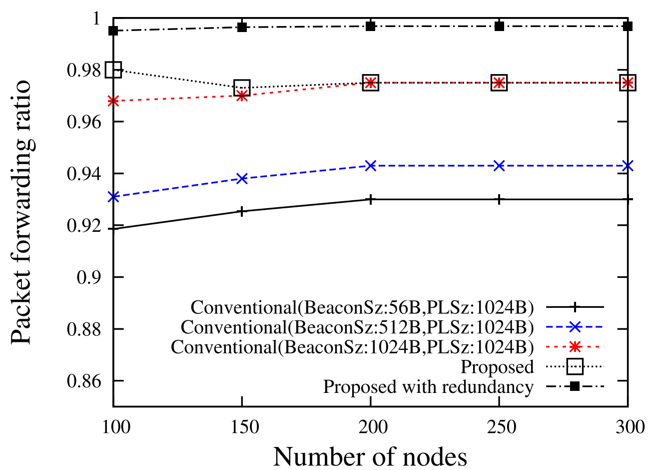

FIGURE 12. **Packet forwarding ratio for various numbers of nodes (payload size = 1024 bytes).**

B. NUMBER OF TRANSMISSIONS

Fig. 13 shows the number of transmissions for various numbers of nodes (when the dissemination distance is 600 m). "Proposed with redundancy and NC(PLSz:1024B)" denotes the performance of the proposed protocol when the network coding is used ($m = 2$, *and* $n = 1$). We observe that the use of redundancy does not increase the number of transmissions significantly, especially when payload size is large (packet forwarding probability is small). This is because the proposed protocol can use a longer-distance node to forward broadcast messages while maintaining high packet forwarding probability by using the redundancy approach. As a result, the protocol can achieve more efficient multi-hop broadcasting. When the network coding is used ("Proposed with redundancy and NC(PLSz:1024B)" in the figure), the proposed protocol can achieve lower number of transmissions as compared with the conventional approach. This is because the network-coding based redundancy approach can reduce

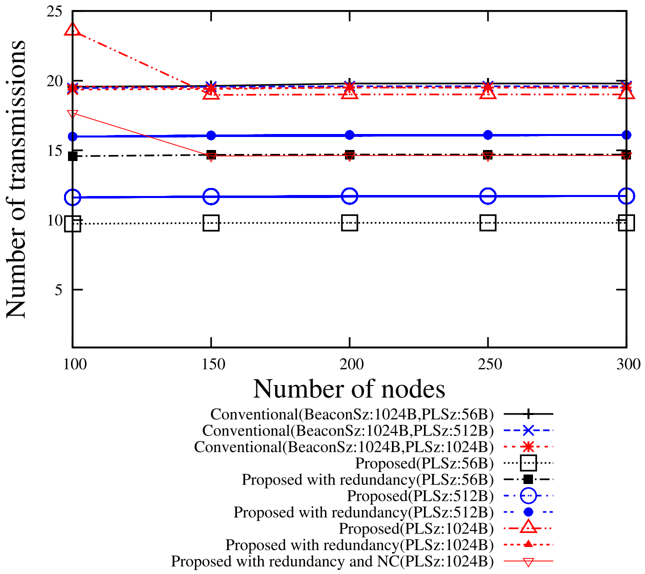

FIGURE 13. Number of transmissions for various numbers of nodes.

the number of required transmissions with little computation cost which is negligible in vehicular networks.

VII. CONCLUSIONS

We examined the effect of packet size on the performance of multi-hop broadcast protocols in real-world VANETs, and then proposed a packet-size aware multi-hop broadcast protocol which utilizes different sizes of beacon packets to precisely estimate the packet forwarding probability for each relay node. The protocol uses a fuzzy logic-based algorithm to select relay nodes and uses a Q-learning based approach to tune the fuzzy membership functions. The protocol also employs a redundancy-based approach to provide high packet forwarding probability. The overhead of the redundancy can be compensated by the efficient multi-hop forwarding which selects forwarder nodes with longer distance as compared with the conventional approach, especially when the network coding is used. Through experimental results and computer simulations, we confirmed the advantages of the proposed protocol over the conventional approach.

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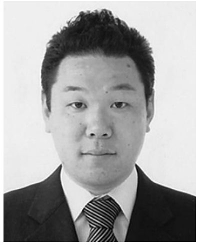
CELIMUGE WU received the M.E. degree from the Beijing Institute of Technology, Beijing, China, in 2006, and the Ph.D. degree from The University of Electro-Communications, Tokyo, Japan, in 2010. He has been an Assistant Professor with the Graduate School of Information Systems, The University of Electro-Communications, since 2010, where he is currently an Associate Professor. His current research interests include vehicular ad hoc networks, sensor networks, intelligent transport systems, IoT, 5G, and mobile cloud computing.

XIANFU CHEN received the Ph.D. degree in signal and information processing from the Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou, China, in 2012. He is currently a Senior Scientist with the VTT Technical Research Centre of Finland, Oulu, Finland. His research interests cover various aspects of wireless communications and networking, with an emphasis on software-defined networking, green communications, centralized and decentralized resource allocation, dynamic spectrum access, and the application of artificial intelligence to wireless communications.

YUSHENG JI (M'94) received the B.E., M.E., and D.E. degrees in electrical engineering from the University of Tokyo. She joined the National Center for Science Information Systems, Japan, in 1990. She is currently a Professor with the National Institute of Informatics, Japan, and Graduate University for Advanced Studies. Her research interests include network architecture, resource management, and performance analysis for quality of service provisioning in wired and wireless communication networks. She is a member of IEICE and IPSJ.

FUQIANG LIU received the bachelor's degree from Tianjin University, in 1987, and the Ph.D. degree from the China University of Mining and Technology, in 1996. He has participated in numerous national research projects in China, and also received research funding from USA, Finland, EU, and Japan. He is currently a Professor with the School of Electronics and Information Engineering, Tongji University, Shanghai, China. He serves as the Director of the Broadband Wireless Communication and Multimedia Laboratory with Tongji University. He is a Guest Professor with the National Institute of Informatics, Tokyo, Japan. He has authored over 300 scientific papers and nine books. His research mainly focuses on theories and technologies of broadband wireless communications (5G mobile communication and vehicular communication/DSRC) and their applications in automotive and intelligent transportation systems.



SATOSHI OHZAHATA (S'00–M'03) received the B.S., M.E., and D.E. degrees from the University of Tsukuba, in 1998, 2000, and 2003, respectively. He was a Research Associate with the Department of Computer, Information and Communication Sciences, Tokyo University of Agriculture and Technology, from 2003 to 2007, where he was also an Assistant Professor from 2007 to 2009. Since 2009, he has been an Associate Professor with the Graduate School of Information Systems, The University of Electro-Communication. His interests are mobile ad hoc networks, the Internet architecture in mobile environments, and Internet traffic measurement. He is a member of ACM and IPSJ.

TSUTOMU YOSHINAGA (M'–) received the B.E., M.E., and D.E. degrees from Utsunomiya University, in 1986, 1988, and 1997, respectively. From 1988 to 2000, he was a Research Associate with the Faculty of Engineering, Utsunomiya University. He was also a Visiting Researcher with the Electro-Technical Laboratory from 1997 to 1998. Since 2000, he has been with the Graduate School of Information Systems, The University of Electro-Communications, where he is currently a Professor. His research interests include computer architecture, interconnection networks, and network computing. He is a member of ACM, IEICE, and IPSJ.

TOSHIHIKO KATO received the B.E., M.E., and D.Eng. degrees in electrical engineering from the University of Tokyo, in 1978, 1980, and 1983, respectively. He joined KDD in 1983, where he was involved in communication protocols of OSI and Internet until 2002. From 1987 to 1988, he was a Visiting Scientist with Carnegie Mellon University. He is currently a Professor with the Graduate School of Information Systems, The University of Electro-Communications, Tokyo, Japan. His current research interests include protocol for mobile Internet, high speed Internet, and ad hoc network.