Joint Fuzzy Relays and Network-Coding-Based Forwarding for Multihop Broadcasting in VANETs

Celimuge Wu, *Member, IEEE*, Satoshi Ohzahata, *Member, IEEE*, Yusheng Ji, *Member, IEEE*, and Toshihiko Kato, *Member, IEEE*

***Abstract*—In vehicular ad hoc networks (VANETs), due to the limited radio propagation range of wireless devices, many safety applications require a multihop broadcast protocol to disseminate traffic warning information. However, providing an efficient multihop forwarding of broadcast messages has been a challenging problem due to vehicle movement, limited wireless resources, and unstable signal strength. In this paper we propose a broadcast protocol that can provide a low message overhead and a high packet dissemination ratio. The proposed scheme uses a fuzzy logic algorithm to choose the next hop relay nodes and uses network coding to improve the packet dissemination ratio without increasing the message overhead. By using the fuzzy logic algorithm, the protocol can choose the best relay node by taking intervehicle distance, vehicle velocity, and link quality into account. Network coding is used to improve the packet reception ratio by utilizing the broadcast nature of wireless channels. We show the effectiveness of the proposed scheme by using both theoretical analysis and computer simulations.**

***Index Terms*—Broadcast protocols, fuzzy logic, network coding, vehicular ad hoc networks.**

I. Introduction

VEHICULAR ad hoc networks (VANETs) have been attracting interest for their potential role in intelligent transport systems. In a VANET, a multihop broadcast protocol is required for many applications such as a collision warning system. Due to the various vehicle densities for different road segments, providing an efficient broadcast protocol is a well-known and challenging problem. When the vehicles are densely distributed, eliminating redundant broadcasts is particularly important. When the network is sparsely connected, it is important to improve the packet reception ratio through the cooperation of receivers in the neighborhood.

Since redundant broadcasts can cause a high packet collision probability and long end-to-end delay, many protocols have been proposed to eliminate redundant broadcasts. These protocols can be classified into two categories: receiver-oriented protocols and sender-oriented protocols.

In the receiver-oriented protocols, when a packet is received, each node determines whether to forward or not by using an autonomous approach. Wisitpongphan and Tonguz [1] have proposed three receiver-based broadcast schemes: weighted p-persistence, slotted 1-persistence, and slotted p-persistence. There are also a number of other approaches [2]–[4]. Since the receiver-based protocols always use a stochastic approach to make a forwarding decision, they cannot eliminate redundant broadcasts in high-density networks and cannot ensure successful packet forwarding in low-density networks. Therefore, in this paper, we use a sender-oriented approach.

In sender-oriented protocols, the sender node specifies the relay nodes before packet delivery. Generally, the selection of relay nodes is based on the information collected from exchanging hello messages among neighbor nodes. Sahoo *et al.* [5] have proposed Binary Partition Assisted Emergency Broadcast Protocol, which aims to use the most distant node in the intended direction to relay messages. However, in a fading channel, the use of the most distant node results in lost messages. The same problem exists in [6] and [7]. Some studies focus on modeling of vehicle-to-vehicle Ricean fading channels [8], [9]. However, the multihop broadcast problem in fading channels is not discussed. The research in [10] considers vehicle movements in the selection of the relay node. Since the link quality is also an important point, in our previous work we proposed FUZZBR [11], a fuzzy-logic-based [12] broadcast protocol, which chooses a relay node by taking intervehicle distance, vehicle movement, and signal strength into account. Due to the dynamic network topology and channel fading, packet loss could also occur at a forwarder node. In FUZZBR, retransmissions are used when a packet is lost at a relay node. However, the retransmissions are inefficient in terms of end-to-end delay and message overhead. To improve the packet reception ratio at the receivers without increasing the message overhead, we use a network-coding-based approach in this paper.

Network coding has been attracting interest in wireless networks due to its potential to utilize the broadcast nature of wireless channels. There have been many protocols applying the ideas derived from network coding [13]–[16]. The studies reported in [13]–[16] are not aimed at VANETs. Nguyen *et al.* [17] have analyzed the benefit of network coding in single-hop wireless networks. Li *et al.* [18] have applied network coding to a deterministic broadcast (sender-oriented) protocol. In a multihop network, the protocol performance can be improved

Manuscript received December 2, 2013; revised April 17, 2014 and September 10, 2014; accepted October 16, 2014. Date of publication November 4, 2014; date of current version May 29, 2015. The Associate Editor for this paper was X. Cheng.

C. Wu, S. Ohzahata, and T. Kato are with the Graduate School of Information Systems, The University of Electro-Communications, Tokyo 182-8585, Japan (e-mail: clmg@is.uec.ac.jp; ohzahata@is.uec.ac.jp; kato@is.uec.ac.jp).

Y. Ji is with the Information Systems Architecture Research Division, National Institute of Informatics, Tokyo 101-8430, Japan (e-mail: kei@nii.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TITS.2014.2364044

1524-9050 © 2014 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

by using cooperation among neighbors, an option that is not considered in [17] and [18]. Some protocols have employed network coding to improve content distribution performance in lossy wireless networks [19]–[22]. These studies focus on performance when downloading large files, which is a different aim from that of this research. Joint operation between data forwarding (relay node selection) and network coding has not been clarified in these previous studies [13]–[22]. Erasure coding is another approach to improve reliability [23], [24]. The main advantage of network coding over erasure coding is that network coding allows intermediate nodes to reencode packets, which is a more efficient approach for multihop networks.

This paper proposes a joint relay node selection and network coding assisted cooperative forwarding protocol for multihop broadcasting in VANETs. We show the advantages of the protocol over existing alternatives using a theoretical analysis and network simulation. In the proposed protocol, each sender node selects the next relay nodes by using a fuzzy logic algorithm. The source node (the source of the network flow) encodes the data packets before transmissions using a linear network coding algorithm. The network coding is conducted for a batch of m ($m = 2$ by default) packets. The source node selects k ($k = 2$ by default) relay nodes. Each relay node specifies the next relay node. By utilizing network coding and cooperation among relay nodes, the proposed protocol can improve the packet dissemination ratio significantly. This paper is an extension of our previous conference paper [25]. In this paper, we present a more in-depth description of the protocol and evaluation results that have not been reported previously.

The remainder of this paper is organized as follows. In Section II, we present a brief outline of related work. In Section III, we describe the notations and system model. In Section IV, we provide a detailed description of the proposed mechanism. Next, we present theoretical analysis and simulation results in Sections V and VI, respectively. Finally, we present our conclusions in Section VII.

II. Related Work

A. Receiver-Oriented Broadcast Protocols for VANETs

Wisitpongphan and Tonguz [1] have proposed three receiver-based broadcast schemes: weighted p-persistence, slotted 1-persistence, and slotted p-persistence. In these protocols, upon reception of a message, a node calculates the broadcast probability by taking the intervehicle distance into consideration. A node at a greater distance (from the sender node) is granted higher broadcast probability in order to provide faster dissemination. Suriyapaiboonwattana *et al.* [2] have proposed an approach that can adaptively tune the forwarding probability by overhearing the transmissions happening in the neighborhood. Slavik and Mahgoub *et al.* [3] have discussed the tuning of stochastic broadcasts in relation to vehicle density. In the speed adaptive probabilistic flooding algorithm, a protocol calculates the forwarding probability by taking the vehicle velocity into account [4]. However, none for these protocols can provide a stable and efficient forwarding scheme in vehicular networks in which vehicle density varies with road segments and time.

B. Sender-Oriented Broadcast Protocols for VANETs

Sahoo *et al.* [5] have proposed a protocol in which each sender node delegates the forwarding duty to the farthest vehicle by employing a binary partition approach. Suthaputchakun *et al.* [6] have proposed the trinary partition approach, which is a modification of the binary partition approach presented in [5]. The profile-driven adaptive warning dissemination scheme (PAWDS) is presented in [7]. PAWDS 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. The proposal presented in [10] selects relay nodes in consideration of vehicle movements in order to provide a stable relay node. These protocols [5]–[7], [10] intend to use the farthest node to forward broadcast data packets when other metrics are the same. This results in a 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 [11] selects relay nodes by considering multiple metrics, namely, the intervehicle distance, vehicle movement, and signal strength. FUZZBR retransmits a broadcast packet when the packet fails to reach the selected relay node. However, the retransmissions increase the message overhead and end-to-end delay, something that could be fatal when there is strict bandwidth or delay constraint.

C. Network Coding in VANETs

Nguyen *et al.* [17] have employed network coding schemes to reduce the number of broadcast transmissions from one sender to multiple receivers. A multihop forwarding scheme is not discussed in [17]. Li *et al.* [18] have examined how network coding can be applied to reduce the number of transmissions in a deterministic broadcast protocol and proposed two network coding algorithms. In a multihop network, in order to improve the end-to-end performance, network coding can be applied by utilizing cooperation among neighbors, which is not considered in [17] and [18]. Yu *et al.* [19] have employed a rank-based network coding scheme for distributing content in VANETs. In this scheme, a node adaptively injects packets into the network based on the content reception status of their neighbors. A network-coding-based file swarming protocol is proposed in [20]. VANETCODE [21] utilizes a network coding scheme to introduce randomization in order to make content distribution more efficient. Li *et al.* [22] have presented CodeOn, a push-based content distribution scheme for VANETs. These studies [19]–[22] have focused on performance when downloading large files and are not designed for multihop broadcast applications. None of these protocols discusses the use of network coding for cooperative multihop broadcast protocols in VANETs.

III. Notation, Linear Network Coding, and the System Model

A. Notation

We summarize the notation in Table I. We use the number of transmissions to denote the number of total transmissions, including original transmissions and retransmissions. The packet dissemination ratio is calculated by dividing the number of data packets received (by all nodes) by the multiplication of the

TABLE I
NOTATION

p_l	link loss rate
T	retransmission time interval (40 ms by default)
R	average transmission range
MF	mobility factor
DF	distance factor
$RSSIF$	received signal strength indication factor
α	smoothing factor (0.7)
m	number of native packets for each generation
k	number of relay nodes
F	probability of successful forwarding for a batch of packets (conventional)
F'	probability of successful forwarding for a batch of packets (proposed)
$\hat{PF}$	probability of successful forwarding (proposed)
PR	packet reception probability at a non-relay node (conventional)
$\hat{PR}$	packet reception probability at a non-relay node (proposed)
N	number of transmissions (conventional)
$\hat{N}$	number of transmissions (proposed)
P_x	packet loss probability at xth transmission (conventional)
D	retransmission incurred delay (conventional)
$\hat{D}$	retransmission incurred delay (proposed)
H	number of hops
n	maximum number of retransmissions
ρ	number of nodes in each road segment of length R
f	number of broadcast flows in each road segment of length R
P_{col}	collision probability
CW	contention window

number of data packets generated at the source nodes and the number of nodes in the network.

B. Linear Network Coding

Linear network coding [26] is a technique that applies linear transformation to a block of data before sending. Due to the broadcast nature of wireless communications, network coding can be used to reduce the number of transmissions.

Suppose a sender node has m native packets to send to multiple receivers. We use $X = (x_i, x_2, \ldots, x_m)^T$ to denote these packets. The sender can construct a batch of linearly coded packets $Y = CX$ as

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_l \end{pmatrix} = \begin{pmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,m} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{l,1} & c_{l,2} & \cdots & c_{l,m} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} \tag{1}$$

where C represents the coding vectors. A receiver can retrieve the corresponding native packets (original packets) when the receiver receives the same or more than m linearly independent packets. The coding vectors are chosen from a Galois field. If the field size is sufficiently large, we can obtain linearly independent m combinations using random selections.

C. System Model

The proposed protocol uses only a subset of nodes in the network to relay broadcast packets. Before broadcasting a packet, a sender node attaches the addresses of the relay (forwarder) nodes to the packet. Upon reception of a packet, a node rebroadcasts the packet only if it is itself included in the relay node list. Vehicles exchange information through hello messages. Every vehicle inserts its own position information in the hello messages. We assume that every node knows its own position and road map information because it is possible to get this position information from GPS positioning services.

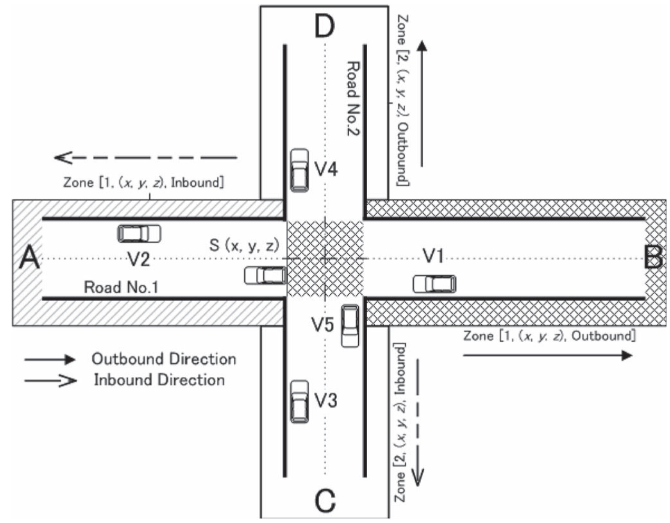

Fig. 1. Topology of an urban street and definition of road zone.

In this paper, we consider network coding in broadcast communications in multihop VANETs. We only consider intraflow network coding (interflow network coding is outside the scope of this paper). Network-wide broadcasting can be classified into several subproblems where each subproblem is a broadcast problem for a broadcast zone.

Each sender node first groups neighbor vehicles according to broadcast zone. The broadcast zone (first presented in [11]) is defined by a triad [road_no, sender_pos, direction]. "road_no" denotes the road number, "sender_pos" denotes the sender position, and "direction" can be "outbound" or "inbound." For example, the triad [1, (x, y, z), outbound] shows the area in which road No.1 is located and the outbound direction of position (x, y, z).

We note that outbound and inbound are predefined for each road. For a loop-free road, since the start point and end point can be defined, we define the direction from the start point to the end point as outbound and define the direction from the end point to the start point as inbound. For a loop road, we define the clockwise direction as outbound and the counterclockwise direction as inbound. As shown in Fig. 1, for road No.1, the direction from A to B is the outbound direction, and from B to A is the inbound direction. Here, outbound and inbound depend on the position of the vehicles but are independent of the driving direction of the vehicles. We say V1 is traveling in the outbound direction of node V2. In contrast, V2 is traveling in the inbound direction of node V1.

By introducing the concept of broadcast zone, the broadcast in VANETs can be divided into several subproblems of directed broadcasts. In each problem, each sender node (the source node or the relay node) specifies the next relay nodes until all receivers are reached.

IV. Proposed Protocol

A. Protocol Overview

The proposed protocol, i.e., fuzzy logic based broadcast with network coding (FUZZBR-NC), specifies relay nodes to forward a packet. FUZZBR-NC selects relay nodes by considering the multiple metrics of intervehicle distance, node mobility, and signal strength based on the fuzzy logic algorithm proposed in [11].

In the proposed protocol, the source node specifies k ($k = 2$ by default) relay nodes for each broadcast zone. The source node processes network coding based on a batch of m ($m = 2$ by default) packets (we say that these m packets belong to the same generation). For simplicity, we use the case of $m = 2$, $k = 2$ to explain the proposed protocol. The performance for different values will be explained in Sections IV-G and V.

The source node uses network coding to encode two consecutive native packets to get two encoded packets and transmits the encoded packets. Upon reception of a packet, a relay node may either reencode the packet or directly rebroadcast the packet depending on the reception status. If the node successfully receives both packets, the node rebroadcasts the linear combinations of the received encoded packet (reencoding). If the node only receives one of the two packets, it is impossible to decode or reencode. In this case, the node rebroadcasts the packet without reencoding. Each node, including relay nodes, can retrieve the native packets if the node receives any two encoded packets. By using the network coding assisted relay scheme, the packet dissemination ratio can be significantly improved.

B. Relay Node Selection

Upon reception of a hello message from a neighbor, each node evaluates the neighbor according to the intervehicle distance, vehicle mobility, and signal strength using a fuzzy-logic-based [12] approach. This way, through exchanging hello messages, each node retains an evaluation result for each neighbor. When selecting a relay node, these evaluation results are used. We use fuzzy logic here because it allows imprecise or contradictory inputs. A fuzzy system is easily tunable by changing the fuzzy membership function and rules. These features make the fuzzy system usable, flexible, and easier to design. While we do not claim that there is no better solution than using fuzzy logic in a specific scenario, alternative solutions are not flexible enough to be used in a highly dynamic VANET environment. Depending on the road type and traffic conditions, the parameters for a VANET protocol should be tuned in order to provide a good outcome. The fuzzy logic approach can provide an easy and flexible approach, and it is possible to tune the fuzzy membership functions and rules to make the protocol more suitable for a certain scenario (such parameter tuning is outside the scope of this paper).

For each neighbor, the calculation steps are as follows.

- *Step 1: Fuzzification*—Use predefined linguistic variables and membership functions to convert the distance factor, the mobility factor, and the received signal strength indication (RSSI) factor to fuzzy values.
- *Step 2: Mapping and combination of IF/THEN rules*—Map the fuzzy values to predefined IF/THEN rules and combine the rules to get the rank of the neighbor as a fuzzy value.
- *Step 3: Defuzzification*—Use a predefined output membership function and defuzzification method to convert the fuzzy output value to a numerical value.

After calculating the relay fitness values for all neighbors, the sender node selects the node that has the maximal fitness value to relay the packet to a particular zone.

1) Metrics: The distance factor, the mobility factor, and the RSSI factor are taken into consideration. Upon reception of a hello message from a neighbor X, a node calculates a distance factor (DF) as in (2). In (2), $d(X)$ is the distance between the current node and node X. R is the average transmission distance. Thus

$$\mathrm{DF}(X) = \begin{cases} \frac{d(X)}{R}, & d(X) \leq R \\ 1, & d(X) > R. \end{cases} \tag{2}$$

Mobility factor (MF) is calculated as (3), where MF indicates the mobility level of the neighbor node. The higher the MF value, the more stable the neighbor node is. Here, $d_i(X)$ is the distance between the current node and the neighbor node at time i. The smoothing factor α is set to 0.7. This parameter limits how quickly the averaged value can change when there is a change in network topology. If the value is too large, the estimation (of mobility) could be affected by an immediate misleading value, which does not show long-term mobility. We know 0.7 is the most suitable value for α after a lot of simulations and analysis. MF is initialized to 0. Thus

$$\mathrm{MF}(X) \leftarrow (1-\alpha) \times \mathrm{MF}(X) + \alpha \times \left(1 - \frac{|d_i(X) - d_{i-1}(X)|}{R}\right). \tag{3}$$

RSSIF is calculated as (4), where RxPr is the received signal power, and RXThresh is the reception threshold. The value of RXThresh is defined based on received power, and a hello message cannot be received when the received power is lower than this value. RSSIF indicates the average signal strength of the neighbor node. Here, RSSIF is initialized to 0. Thus

$$\mathrm{RSSIF}(X) \leftarrow (1-\alpha) \times \mathrm{RSSIF}(X) + \alpha \times \left(1 - \frac{\mathrm{RXThresh}}{\mathrm{RxPr}}\right). \tag{4}$$

2) Fuzzification: The corresponding fuzzy membership functions are defined, as shown in Fig. 2.

3) Rule Base: Once the fuzzy values of the distance factor, the mobility factor, and the RSSI factor have been calculated, the sender node uses the IF/THEN rules (as defined in Table II) to calculate the rank of the node. The linguistic variables of the rank are defined as {Perfect, Good, Acceptable, NotAcceptable, Bad, VeryBad}. For example, in Table II, Rule1 may be expressed as follows.

IF *Distance* is Large, *Mobility* is Slow, and *Signal Strength* is Good, **THEN** *Rank* is Perfect.

Since there could be multiple rules that apply at the same time, we use the min–max method to combine their evaluation results.

4) Defuzzification: The output membership function is defined, as shown in Fig. 3. Here, we use the center of gravity (COG) method to defuzzify the fuzzy result. For the example given above, the degree for Rank {Acceptable} is 0.25, the degree for Rank {Good} is 0.5, and the degree for Rank {Perfect} is 0.5, and consequently, the result function will form the shape shown in Fig. 3. Then, we calculate the centroid of this shape. The x coordinate of the centroid will be the final defuzzified value. If we use $\mu(x)$ to denote the result function and use x to denote the X-axis, the center of gravity will be

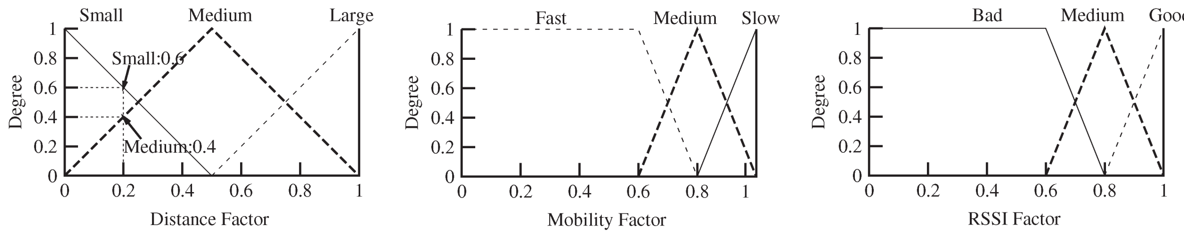

Fig. 2. Fuzzy membership functions [(left) DF; (middle) MF; (right) RSSIF].

TABLE II
RULE BASE

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

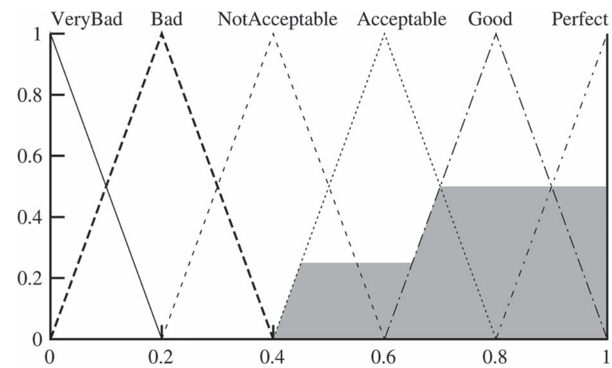

Fig. 3. Output membership function and an example of $\mu(x)$.

$\mathrm{COG} = \int \mu(x)x dx / \int \mu(x) dx$. The value represents the fitness of the neighbor to be a relay node. The higher the value, the higher the fitness of the neighbor node is.

C. Packet Encoding at the Source Node and Relay Nodes

In the proposed protocol, the coding vectors are selected from

$$C = \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \\ 2 & 3 \\ 3 & 5 \end{pmatrix}. \quad (5)$$

Therefore, when the native packets are a and b, the possible encoded packets (with field size of GF(2^3)) are

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \\ 2 & 3 \\ 3 & 5 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a+b \\ a+2b \\ 2a+3b \\ 3a+5b \end{pmatrix}. \quad (6)$$

Since there are two packets for each generation, any two of coding vectors $C = (c_1, c_2, c_3, c_4)^T$ could be used for encoding the packets. The source node encodes the packets using any two coding vectors. The benefit of using these coding vectors is that we can transform any two encoded packets into two other encoded packets. For example, we can get (y_3, y_4) from (y_1, y_2). This is very useful for improving the packet dissemination ratio through cooperation among neighbors because each node can decode the packets provided the node receives any two packets.

All nodes share the same coding vector C. The identifier of the used coding coefficients and the identifier of original packets (information vector) are transmitted with the coded packets. Note that this is more practical for real application than random coefficients because the independence between different coded packets is ensured. The coding vectors can be shared at the protocol deployment phase because the vectors do not need to change in the middle of protocol execution. These coding vectors can be also updated using broadcast communications initialized by an authorized party. We can also design a larger vector and choose to use some of them depending on the situation.

D. Network Coding Assisted Cooperative Relay Scheme

In the proposed protocol, the source node specifies two relay nodes for each broadcast zone. The source node processes network coding based on a batch of two packets. The source node uses the network coding algorithm to encode two consecutive packets and then transmits them. Upon reception of a packet, each node performs the actions as shown in Algorithm 1.

Algorithm 1 Actions at each relay node upon reception of an encoded packet

```
if (The packet is the first packet of this generation) then
    Wait for a short time period to check whether the second
    encoded packet could be received or not.
    if (The second encoded packet is successfully received)
    then
        if (A rebroadcast at the other relay node is confirmed)
        then
            Transform the encoded packets to a new encoded
            packet (any one of two other different linear com-
            binations), and transmit the new packet.
        else
            Transform the two encoded packets to get two new
            encoded packets (with two different linear combi-
            nations), and transmit these new packets (however,
```

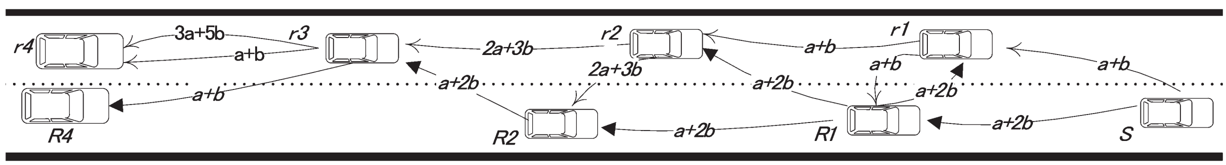

Fig. 4. Network coding assisted relay scheme in the proposed protocol.

if a rebroadcast at the other relay node is confirmed after the first transmission, the second packet would be canceled).

end if

else

Rebroadcast the received encoded packet.

end if

else

if (Any rebroadcast of the packet is detected) **then**

Transform the encoded packets to a new encoded packet (any one of two other different linear combinations), and transmit the new packet.

else

Transform the encoded packets to get two new encoded packets (other two different linear combina tions), and transmit these new packets consecutively (by specifying different relay nodes for different packets).

end if

end if

As shown in Fig. 4, the source node S encodes the packets (a, b) to get the linear combinations $(a + b, a + 2b)$. Here, for node S, all other nodes belong to the same broadcast zone because all other nodes are located to the left of node S on the same road. The source node S selects two relay nodes $r1$ and $R1$. Let us assume that node $r1$ only received $a + b$ and node $R1$ only received $a + 2b$ due to a lossy channel. In this case, nodes $r1$ and $R1$ rebroadcast the packets they received. After that, nodes $r1$ and $R1$ can receive one packet from each other and successfully decode to get the original native packets. The packet forwarding is also transferred to the next hop relay nodes $r2$ and $R2$. Here, since $r2$ receives two encoded packets, the node transforms the two received packets to get a new linear combination of native packets $(2a + 3b)$. Node $R2$ can get the original packets by decoding $(2a + 3b, a + 2b)$. Typically, since each node is aware of the communications happening in the neighborhood, it is possible to select a different relay node from other nodes. In the case when both $r2$ and $R2$ select the same node $r3$ as the next relay node (when there is no other choice), node $r3$ selects the next two relay nodes (which are nodes $r4$ and $R4$). This happens very rarely in real-world scenarios, particularly in high-density networks.

E. Retransmissions

The packet reception probability at the next hop nodes can be improved by using the proposed network-coding-based cooperative forwarding approach. However, packet loss could still

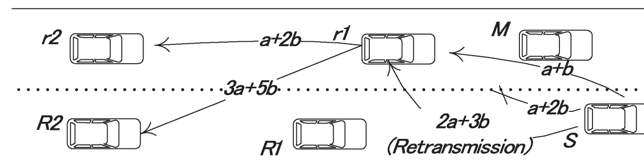

Fig. 5. Network-coding-based retransmissions.

occur due to bad link quality or collisions with other packets. In order to further improve the packet dissemination ratio, the proposed protocol retransmits a packet when the sender node fails to detect the corresponding forwarding at the next relay node within a predefined retransmission time interval T (40 ms by default). Note that the sender node does not need to select a new relay node because the possible movement of vehicles in interval T is negligible compared with the transmission range. The relay node selection takes account of vehicle mobility and received signal strength, which ensures that the relay node can receive a packet within a relatively extended period of time. The proposed protocol is different from the conventional retransmission approach where only the lost packet can be retransmitted. Instead, the proposed protocol retransmits a different encoded packet (an encoded packet of the two original packets) from the previously transmitted packets. As shown in Fig. 5, the sender node S first transmits two encoded packets, which are $a + b$ and $a + 2b$, respectively. When packet $a + 2b$ is lost, node S transmits $2a + 3b$, which is a different encoded packet from $a + b$ and $a + 2b$. Assuming one packet is received at node $r1$ (in the figure, the packet is $a + b$), regardless of which packet is lost, a node can recover the original packets when the node receives $2a + 3b$. Therefore, by encoding the packet before retransmission, the proposed protocol can reduce the number of transmissions by one compared with the conventional retransmission approach. The reception probability at node M is also improved by using the proposed retransmission approach (node M can retrieve the original packet if the node can receive any two of three transmissions). Note that overhearing errors could occur when link quality is poor. In this case, the proposed protocol can significantly reduce the number of retransmissions.

Since in vehicular networks the probability of packet loss could be very high [27], we set the maximum number of retransmissions for each pair of packets at three by default (note that this parameter can be tuned according to the network environment and application requirements).

F. End-to-End Delay Consideration

The proposed protocol sends data with encoding based on a batch consisting of two packets. This raises the concern of a possible delay to the first packet. However, in real-world scenarios, it is always impossible for one packet to contain all the necessary information that needs to be broadcasted. There are always two or more packets arriving consecutively in the send queue. This means that batch processing does not incur too much delay. Moreover, with network coding, many retransmissions can be avoided, which also reduces retransmission delays.

G. Parameter Tuning and Extension

The values of m and k can be changed according to the application requirements. The field size and the generation size (m) have a significant impact on the performance of network coding [28], [29]. In the proposed protocol, when m is 2, the field size is GF(2^3). Since we use deterministic coding vectors, which are linearly independent, the proposed protocol is more efficient than linear network-coding-based approaches, which always require larger field size (GF(2^8) or larger) and larger generation size (16 or larger) [29]. Moreover, when m is large, a receiver node needs to wait longer before decoding the encoded packets. Therefore, we set m to 2 by default. A larger value of k can improve reliability. However, the possibility of redundant transmissions is a concern. In a sparse network, the number of possible relay nodes is also limited. Considering generality, we set k to 2 by default. The analysis for different values of m and k will be shown in Section V.

The proposed protocol employs a network coding assisted relay scheme, which can provide multihop forwarding of broadcast packets in VANETs with low overhead. The performance of the proposed protocol can be improved further by using cooperation between the relay node selection algorithm and the network coding assisted relay scheme. There are two approaches to enhance the mutual cooperation. The first approach is tuning the fuzzy parameters according to the possible network coding gain in order to enhance the forwarding process. For example, if the network coding scheme can provide a very high packet forwarding probability, a longer distance node is preferred as a relay node. The other approach is tuning the number of native packets for each generation (m) and the number of relay nodes (k) by considering the link quality at the relay node candidates. We use the latter approach because it is easier to implement. As we will show in Section V later, since k is the dominant factor for the forwarding process, we increase k when the current m and k cannot satisfy the forwarding probability constraint [(11) can be used to calculate the forwarding probability for specific m and k]. The constraint (0.98 by default) can be defined based on the application requirement.

In the proposed protocol, we take into account intervehicle distance, vehicle mobility, and received signal strength for the relay selection. The values for these parameters and the fuzzy parameters (fuzzy membership functions and fuzzy rules) are defined based on our experience and simulation results. It is possible to tune these parameters to make the protocol more suitable for a certain scenario by changing the fuzzy parameters. In addition, we can easily extend the protocol to take additional metrics into consideration. However, such parameter tuning is outside the scope of this paper.

V. Theoretical Analysis

A. Probability of Successful Forwarding

We first analyze the case of typical sender-oriented protocols. The relay nodes are specified by the upstream sender node. For a fair comparison, we assume that only one relay node is selected (in the proposed protocol, the average number of relay nodes for each packet is the same because two relay nodes are selected for two packets). If the packet loss probability of the link is p_l (for simplicity, we assume that this probability is constant), the probability for successful forwarding of two consecutive packets is

$$F_{(2)} = (1-p_l)^2. \tag{7}$$

In the proposed protocol, the probability is

$$F'_{(2,2)} = 1 - p_l^4 - \binom{4}{1}(1-p_l)p_l^3 - \binom{2}{1}(1-p_l)^2 p_l^2. \tag{8}$$

The rationale behind this is that the forwarding (in the proposed protocol) only fails when 1) the total number of received packets at two relay nodes is less than two; or 2) two relay nodes receive only one packet, and the packets received at two relay nodes are the same. When p_l is 0.1, this probability is 0.9801. However, without network coding, we get only 0.81 according to (7).

We can easily extend the analysis for m consecutive packets and k relay nodes, as in

$$\begin{aligned}
F'_{(3,2)} &= 1 - p_l^6 - \binom{6}{1}(1-p_l)p_l^5 - \binom{6}{2}(1-p_l)^2 p_l^4 \\
&\quad - \binom{6}{3}(1-p_l)^3 p_l^3 \left(\frac{\binom{3}{1}\binom{4}{3}}{\binom{6}{3}}\right) \\
&\quad - \binom{6}{4}(1-p_l)^4 p_l^2 \left(\frac{\binom{3}{1}\binom{4}{4}}{\binom{6}{4}}\right) \\
&\quad \cdots\cdots \\
F'_{(m,2)} &= 1 - \left(\sum_{i=0}^{m-1}\binom{2m}{i} p_l^{2m-i}(1-p_l)^i\right) \\
&\quad - \left(\sum_{i=m}^{2m-2}\binom{2m}{i} p_l^{2m-i}(1-p_l)^i \left(\frac{\binom{m}{1}\binom{2m-2}{i}}{\binom{2m}{i}}\right)\right) \qquad (9) \\
F'_{(2,3)} &= 1 - p_l^6 - \binom{6}{1}(1-p_l)p_l^5 \\
&\quad - \binom{6}{2}(1-p_l)^2 p_l^4 \left(\frac{\binom{2}{1}\binom{4}{2}}{\binom{6}{2}}\right) \\
&\quad - \binom{6}{3}(1-p_l)^3 p_l^3 \left(\frac{\binom{2}{1}\binom{4}{3}}{\binom{6}{3}}\right) \\
F'_{(3,3)} &= 1 - p_l^9 - \binom{9}{1}(1-p_l)p_l^8 - \binom{9}{2}(1-p_l)^2 p_l^7 \\
&\quad - \binom{9}{3}(1-p_l)^3 p_l^6 \left(\frac{\binom{3}{1}\binom{6}{3}}{\binom{9}{3}}\right)
\end{aligned}$$

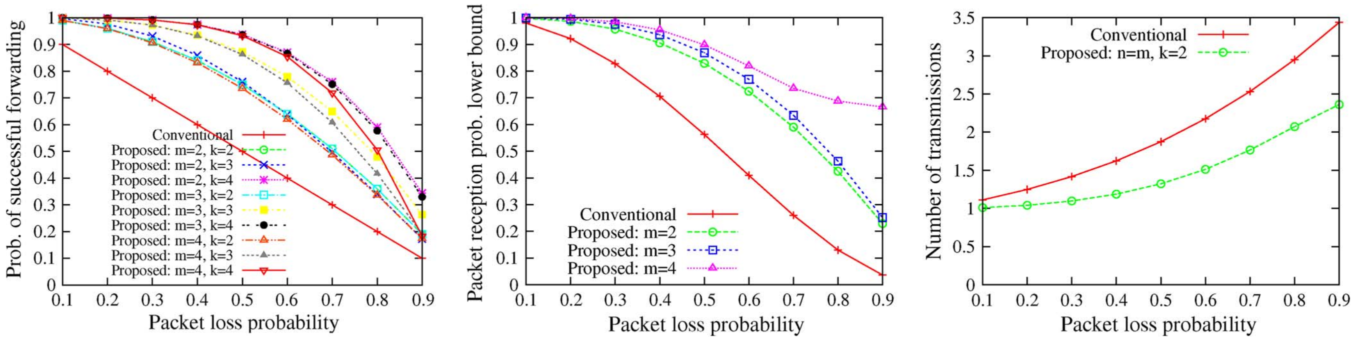

Fig. 6. Theoretical comparison [(left) probability of successful forwarding; (middle) packet reception probability lower bound at a nonrelay node; (right) number of retransmissions for successful delivery of a data packet to the next hop].

$$
\begin{aligned}
&- \binom{9}{4}(1-p_l)^4 p_l^5 \left(\frac{\binom{3}{1}\binom{6}{4}}{\binom{9}{4}}\right) \\
&- \binom{9}{5}(1-p_l)^5 p_l^4 \left(\frac{\binom{3}{1}\binom{6}{5}}{\binom{9}{5}}\right) \\
&- \binom{9}{6}(1-p_l)^6 p_l^3 \left(\frac{\binom{3}{1}\binom{6}{6}}{\binom{9}{6}}\right) \\
&\cdots\cdots
\end{aligned}
$$

$$
\begin{aligned}
F'_{(m,k)} =& 1 - \left(\sum_{i=0}^{m-1} \binom{k \cdot m}{i} p_l^{k\cdot m-i}(1-p_l)^i\right) \\
&- \left(\sum_{i=m}^{k\cdot m-k} p_l^{k\cdot m-i}(1-p_l)^i \binom{m}{1}\binom{k\cdot m-k}{i}\right). \quad (10)
\end{aligned}
$$

The probability of successful forwarding for each packet can be calculated as

$$\hat{\mathrm{PF}}_{(m,k)} = \left(F'_{(m,k)}\right)^{\frac{1}{m}}. \quad (11)$$

We observe that reliability can be improved by increasing k. Each relay node sends a packet when the transmission of the same packet is not detected within a given time period. As a result, when there is a large number of relay nodes, redundant transmissions could occur because multiple relay nodes could send the packet at the same time. On the other hand, in a sparse network, the number of possible relay nodes is limited. Therefore, we set $k = 2$, which is suitable for most scenarios.

B. Packet Reception Probability Lower Bound at a Nonrelay Node

We analyze the lower bound for packet reception probability at receiver nodes (except for the relay nodes). We assume that the data packets are successfully forwarded at the relay nodes. Each node has at least two chances to receive a data packet: one is from the sender node, and the other is from the relay node. Without network coding, the probability lower bound is

$$\mathrm{PR} = 1 - p_l^2. \quad (12)$$

In the proposed protocol, a node can decode the packets when two or more encoded packets are received. Therefore, we can calculate the probability as

$$\hat{\mathrm{PR}}_{(m,k)} = \left(1 - \left(\sum_{i=0}^{m-1}\binom{2m}{i}(1-p_l)^i p_l^{2m-i}\right)\right)^{\frac{1}{m}}. \quad (13)$$

As shown in Fig. 6 (middle), the proposed protocol can significantly improve the packet reception probability at a nonrelay node. When m is larger, the probability is high. However, note that a higher m requires a larger k in order to achieve a high probability of successful packet forwarding [see Fig. 6 (left)].

C. Number of Transmissions for Successful Delivery of a Data Packet to the Next Hop

A retransmission is only triggered when a packet is lost. For the conventional approach (without network coding), the expected number of transmissions for each data packet can be calculated as

$$
\begin{aligned}
P_1 &= p_l \\
P_2 &= p_l^2 \\
P_3 &= p_l^3 \\
N &= 1 + \sum_{i=1}^{n} P_i = 1 + \sum_{i=1}^{n} p_l^i \quad (14)
\end{aligned}
$$

where P_i is the probability of forwarding failure of the ith transmission, and n is the maximum number of retransmissions. In the proposed protocol, the number can be calculated as

$$\hat{N}_{(m,k)} = 1 + \frac{\sum_{i=1}^{n}\prod_{j=1}^{i}\left(1 - F'_{(m,k+j-1)}\right)}{m}. \quad (15)$$

Since the proposed protocol processes packets in a generation of m packets, the number of retransmissions for each data packet is $1/m$ of the number of retransmissions conducted for each generation. This is why the calculation of $\hat{N}_{(m,k)}$ includes the coefficient $1/m$ [see (15)]. As shown in Fig. 6 (right), the proposed protocol can significantly reduce the number of retransmissions, particularly when the probability of packet loss is high.

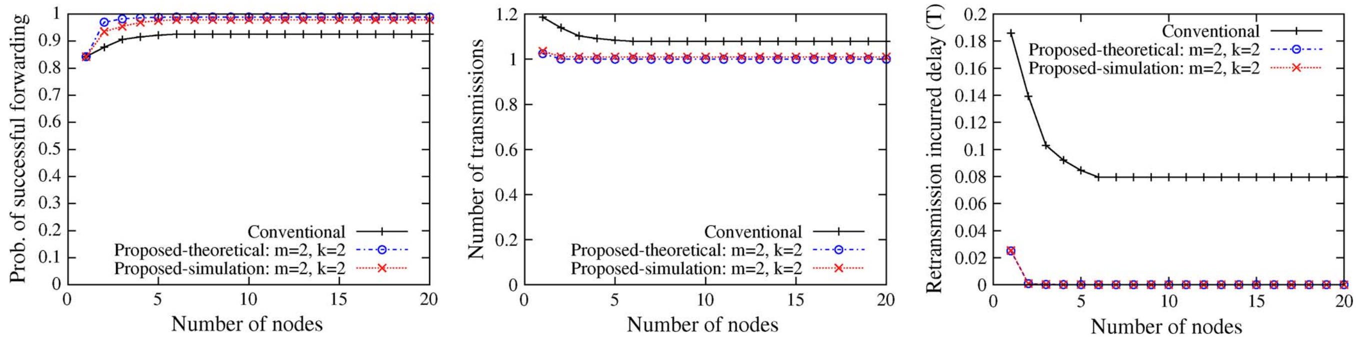

Fig. 7. Performance for various numbers of nodes in the transmission range [(left) probability of successful forwarding (without retransmission); (middle) number of transmissions for each hop; (right) retransmission incurred delay].

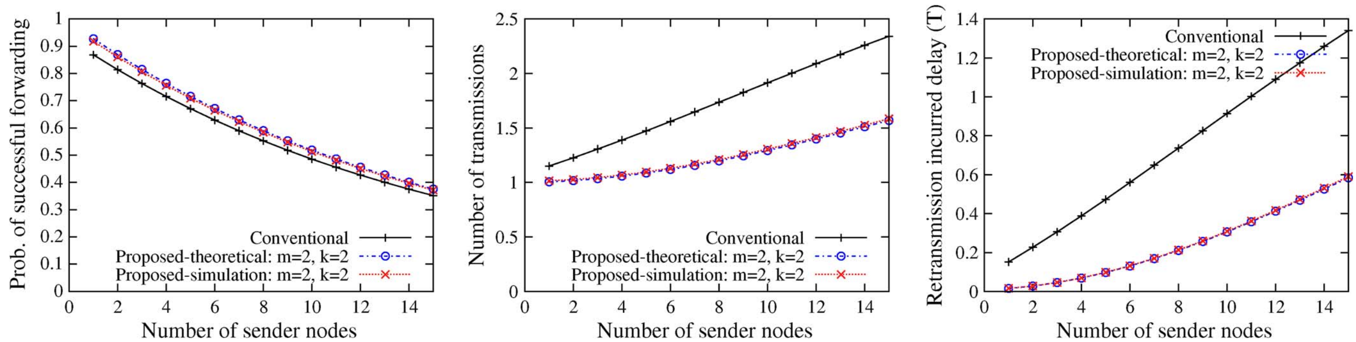

Fig. 8. Performance for various numbers of sender nodes in the transmission range [(left) probability of successful forwarding (without retransmission); (middle) number of transmissions for each hop; (right) retransmission incurred delay].

D. Retransmission Incurred Delay

When data forwarding fails, the sender node has to retransmit the lost packet. Generally, each sender node uses a retransmission timer to detect whether the packet is successfully delivered or not. Considering the overhead, the retransmission timer cannot be set to a very small value. As a result, the retransmission incurred delay is a major contributor to the end-to-end delay, particularly in a lossy network. Based on the analysis in Section V-C, we can calculate the retransmission incurred delay. For the conventional approach, the delay is $D = N \cdot T \cdot H$, where T is the value of retransmission timer, and H is the number of hops. For the proposed protocol, the delay is $\hat{D} = \hat{N}_{(m,k)} \cdot T \cdot H$. The proposed protocol can significantly reduce the delay in comparison with the conventional approach, particularly when the number of hops is large.

E. Effect of Vehicle Density

We use ρ to denote the number of nodes in each road segment with length R, where R is the transmission range. The packet loss probability (p_l) at a relay node is affected by ρ. When ρ is very small, p_l could be very high because the network is sparsely connected. As a result, the proposed protocol could fail to select the second relay node. In this case, the proposed protocol achieves a level of performance similar to that of the conventional approach. However, the proposed protocol also can reduce the number of retransmissions when a packet is lost. When ρ is large enough to select two or more relay nodes, the proposed protocol can attain a significant improvement in performance. Fig. 7 compares the performance of the conventional approach with that of the proposed protocol. "Proposed-theoretical" shows the analytical results based on the equations previously given [see (7)–(15)]. "Proposed-simulation" shows the ns-2 (version 2.34) [30] simulation result for the same parameters (packet reception probability $(1 - p_l)$ is calculated based on Fig. 10, which will be explained later).

F. Effect of the Number of Sender Nodes

Since there are no RTS/CTS for the broadcast frame in the IEEE 802.11p MAC layer, the hidden terminal problem could occur. When f is the number of broadcast flows in each road segment of length R, a transmission at a sender node could possibly collide with f other sender nodes. The collision probability can be calculated as

$$P_{\text{col}} = 1 - \left(1 - \frac{1}{\text{CW} + 1}\right)^f \tag{16}$$

where CW is the current contention window ranging between $\text{CW}_{\min}$ (15) and $\text{CW}_{\max}$ (1023).

Fig. 8 shows the protocol performance for various numbers of sender nodes in the transmission range $(\text{CW} = 15)$. In a real VANET, the number of sender nodes is affected by the number of nodes, hello interval, and the number of broadcast flows. The performance in a more realistic environment will be presented in Section VI. As shown in Fig. 8, the proposed protocol can significantly reduce the number of transmissions by using the network-coding-based transmission approach, which results in a lower packet collision ratio and lower retransmission incurred delay.

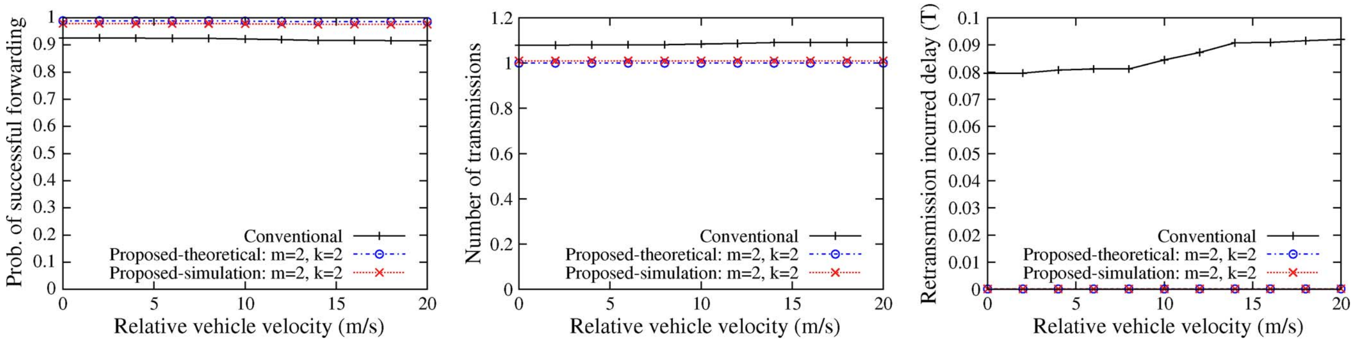

Fig. 9. Performance for different relative velocities of forwarder node [(left) probability of successful forwarding (without retransmission); (middle) number of transmissions for each hop; (right) retransmission incurred delay].

TABLE III
SIMULATION ENVIRONMENT

	Freeway scenario	Street Scenario
Topology	2000 m, 4lanes	1700 m × 1700 m
Number of nodes	20 to 600	619
Mobility generation	Reference [31]	SUMO + TraNS
Number of sources	2	2 to 22
Packet size	512bytes	
Data rate	20 packets per second	15 packets per second
MAC	IEEE 802.11p (3Mbps: plausible broadcast rate)	
Propagation model	Nakagami Model	
Simulation time	150 s	

TABLE IV
PARAMETERS OF THE NAKAGAMI MODEL: FREEWAY (STREET)

gamma0_	gamma1_	gamma2_	d0_gamma_	d1_gamma_
1.9 (2.0)	3.8 (2.0)	3.8 (2.0)	200 (200)	500 (500)
m0_	m1_	m2_	d0_m_	d1_m_
1.5 (1)	0.75 (1)	0.75 (1)	80 (80)	200 (200)

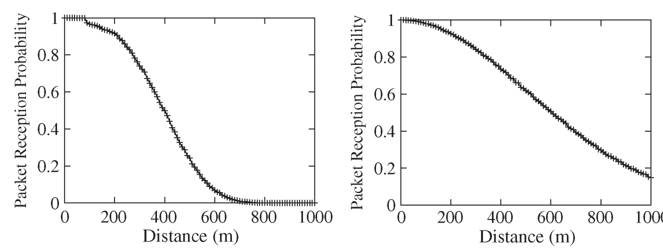

Fig. 10. Packet reception probability for various distances [(left) Freeway scenario; (right) Street scenario].

G. Effect of Vehicle Velocity

The proposed protocol selects relay nodes based on exchange of hello messages. This raises a concern about the effect of relative vehicle velocity (between a sender node and the next forwarder node) on the successful forwarding probability. Since the hello messages are periodically transmitted (the interval is 1 s by default), the intervehicle distance in the time of data packet transmission could be different from that of relay node selection. The increase in intervehicle distance results in lower packet reception probability (the probability can be calculated based on Fig. 10, which will be explained later). Fig. 9 shows the protocol performance for different relative velocities of forwarder node (here, we only consider the case that vehicle movement increases the intervehicle distance). We observe that the proposed protocol is not sensitive to the relative vehicle velocity. This is because the increase in the intervehicle distance in 1 s is limited, and the proposed protocol takes into account the intervehicle distance for the relay node selection.

VI. SIMULATION RESULTS

We used network simulator ns-2 (version 2.34) [30] to conduct simulations. The simulation environment is shown in Table III. We evaluated the protocols' performance in Freeway scenarios and Street scenarios. In the Freeway simulation, we used a freeway with two lanes in each direction. All lanes of the freeway were 2000 m in length. The distance between any two adjacent lanes was 5 m. The maximum allowable vehicle velocity was 40 m/s. The freeway was generated by [31]. We evaluated the protocol's performance for various numbers of nodes. Two source nodes generated packets at a rate of 20 packets per second. These two nodes were neighbors and close to each other. This is to simulate the condition where two adjacent (collided) vehicles send data messages at the same time.

We also used SUMO [32] and TraNS [33] to generate street scenarios. SUMO is a microscopic traffic simulator, and TraNS is a realistic simulation generation tool that integrates SUMO and ns-2. In SUMO, a vehicle's speed is adapted to the speed of the leading vehicle. In our street scenarios, the maximal vehicle velocity was 18 m/s. For each of the street scenarios, we used a street area of 1700 m × 1700 m. The street configuration consisted of five horizontal streets and five vertical streets, and every street had one lane in each direction. The distance between any two neighboring intersections was 400 m. In the Street scenario, 619 nodes were moving toward their destinations (these destinations were randomly selected). Therefore, we can simulate a street that has various node densities on different road segments. We generated scenarios with various numbers of broadcast source nodes.

The average transmission range was 250 m. We used the Nakagami propagation model to simulate channel fading. The parameters of the Nakagami model are shown in Table IV. For each parameter, the first value indicates the parameter value used in Freeway scenarios, and the value between the parentheses indicates the parameter value used in Street scenarios. We used these parameter values because they model a realistic wireless channel (including the effect of buildings) of VANETs [34]. In the model, the reception probabilities for various distances were as shown in Fig. 10.

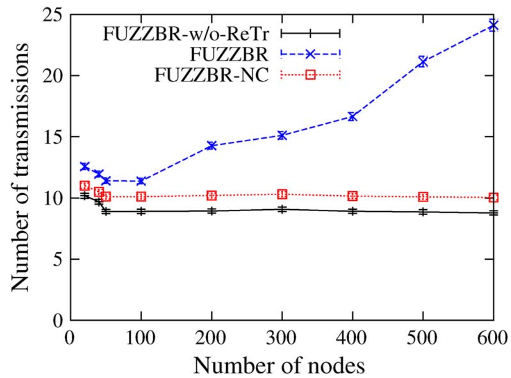

Fig. 11. Number of transmissions per data packet for various numbers of nodes (Freeway).

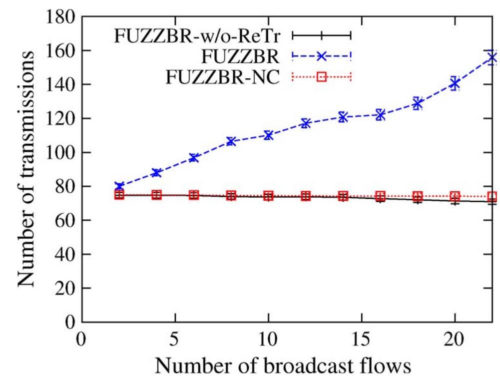

Fig. 12. Number of transmissions per data packet for various numbers of broadcast flows (Street).

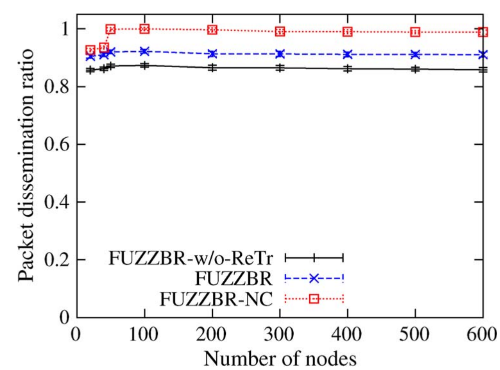

Fig. 13. Packet dissemination ratio for various numbers of nodes (Freeway).

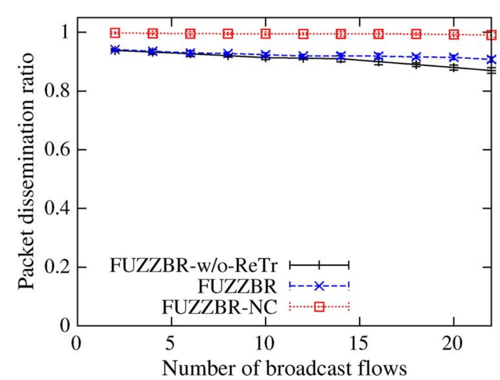

Fig. 14. Packet dissemination ratio for various numbers of broadcast flows (Street).

Other simulation parameters were the default settings of ns-2.34. After the first 20 s (to allow for the exchange of hello messages), senders sent messages with a packet size of 512 B. All nodes in the network were defined as intended receivers (the whole network area was defined as the destination region). The simulation time was 150 s. We performed simulations under 50 different scenarios and analyzed the average value of the results.

The proposed protocol, i.e., FUZZBR-NC, was compared with FUZZBR without retransmissions (FUZZBR-w/o-ReTr) and FUZZBR [11]. FUZZBR is known as a better solution in comparison with other existing approaches, including flooding, weighted p-persistence [1], and enhanced MPR broadcast [10]. In FUZZBR, a sender node retransmits a packet when the forwarding of the packet at a specified relay node is not detected within a predefined time period (40 ms in the simulation). Since a packet might be retransmitted multiple times depending on the reception status, to avoid endless retransmission, for each packet, we set the maximum number of retransmissions at three. In contrast to FUZZBR, FUZZBR-w/o-ReTr does not take any action when packet loss occurs at a relay node. In the following simulation results, the error bars indicate 95% confidence intervals.

A. Number of Transmissions

Fig. 11 shows the number of transmissions (of data packets) per data packet (generated at the source node) for various numbers of nodes in the Freeway scenarios. FUZZBR shows the highest number due to the retransmissions. FUZZBR-w/o-ReTr shows the lowest number of transmissions because many packets are lost at the relay nodes. FUZZBR-NC shows a low message overhead because the network coding assisted cooperative relay scheme can significantly increase the reliability at the relay node while keeping the overhead the same. When the node density is very low, the number of relay candidates is limited. In this case, the packet loss probability at the selected relay node can be high, which results in a higher number of transmissions. The proposed protocol requires fewer retransmissions and therefore achieves lower overhead compared with the conventional retransmission approach (FUZZBR-w/o-ReTr).

Fig. 12 shows the number of transmissions per data packet for various numbers of broadcast flows in the Street scenarios. In FUZZBR, we observe an increase in the number of transmissions as the number of source nodes increases. This is due to the retransmissions following the increase in the number of packet collisions. Due to the network-coding-based approach, FUZZBR-NC shows a very low overhead.

B. Packet Dissemination Ratio

Figs. 13 and 14 show the packet dissemination ratio for the Freeway scenario and the Street scenario, respectively. FUZZBR-NC has the highest packet dissemination ratio. The advantage of FUZZBR-NC over FUZZBR is that the proposed protocol can reduce the number of transmissions. This is very important because redundant transmissions could result in collisions at receivers. Since it is impractical to check the reception

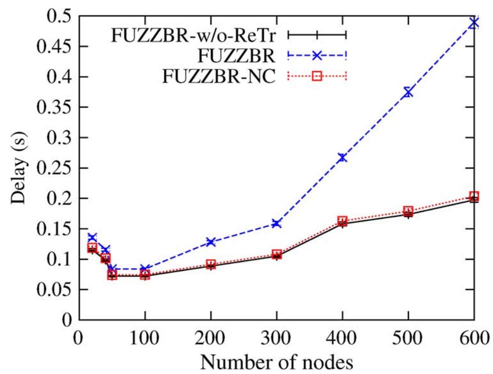

Fig. 15. End-to-end delay for various numbers of nodes (Freeway).

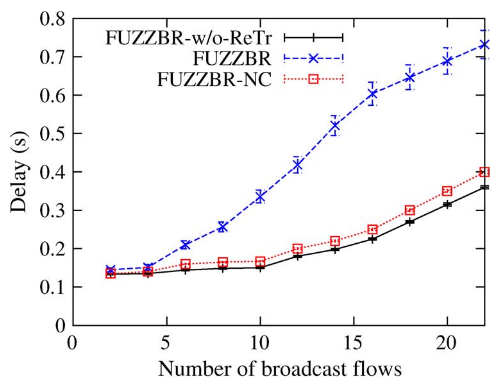

Fig. 16. End-to-end delay for various numbers of broadcast flows (Street).

status of all receivers, we have to reduce the overall redundancy. With the network-coding-based approach, the proposed protocol can improve the packet dissemination ratio with very low overhead.

Although FUZZBR-w/o-ReTr can choose the best relay node to relay a data message, the message could still be lost at the relay node due to the packet collisions. FUZZBR solves this problem by making retransmissions at the sender node. However, the retransmissions incur a high overhead, particularly when traffic is heavy (as shown in Figs. 11 and 12). The network coding approach used in the proposed protocol can significantly increase the packet dissemination ratio. The proposed protocol can recover many lost packets using the cooperative relay scheme.

C. End-to-End Delay

Fig. 15 shows end-to-end delay for various numbers of nodes in the Freeway scenario. FUZZBR incurs high delay due to the retransmission delay. As the node density increases, the MAC layer contention time increases due to the larger number of contending nodes (each node is sending hello messages periodically). The proposed protocol shows a low end-to-end delay for the following two reasons: 1) the proposed protocol reduces the number of transmissions as compared with FUZZBR, and 2) the proposed protocol improves the packet reception probability at the receiver nodes using network coding, which reduces the retransmission incurred delay.

Fig. 16 shows end-to-end delay for various numbers of broadcast flows. In the simulation, without loss of generality, for each data message, all nodes in the network are defined as intended receivers. However, for the Street scenario, it makes no sense to average end-to-end delays for all nodes in the network. We consider that 600 m is the distance within which a short propagation delay is required. Therefore, in the delay calculation, for each source node, we only use the receiver nodes for which the distance from the source node is less than 600 m. The advantage of the proposed protocol over FUZZBR is very significant, particularly when the number of broadcast flows is large. When the network traffic load is high, the retransmission-based approach is not applicable because it requires more bandwidth than the network can provide.

VII. Conclusion

We have proposed a multihop broadcast protocol for VANETs. The protocol employs a joint fuzzy relay selection and network-coding-based forwarding scheme. The relay nodes are selected using a fuzzy logic algorithm that takes intervehicle distance, vehicle movement, and received signal strength into account. The relay nodes cooperate with each other to recover lost packets by employing a network coding algorithm to encode packets. The theoretical analysis and simulation results showed that the proposed scheme can significantly improve the packet dissemination ratio and reduce the end-to-end delay while maintaining a low overhead.

References

[1] N. Wisitpongphan and K. O. Tonguz, "Broadcast storm mitigation techniques in vehicular *ad hoc* networks," *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 84–94, Dec. 2007.

[2] K. Suriyapaiboonwattana, C. Pornavalai, and G. Chakraborty, "An adaptive alert message dissemination protocol for VANET to improve road safety," in *Proc. IEEE Int. Conf. Fuzzy Syst.*, 2009, pp. 1639–1644.

[3] M. Slavik and I. Mahgoub, "Stochastic broadcast for VANET," in *Proc. IEEE Consum. Commun. Netw. Conf.*, 2010, pp. 1–5.

[4] Y. Mylonas, M. Lestas, and A. Pitsillides, "Speed adaptive probabilistic flooding in cooperative emergency warning," in *Proc. 4th Annu. Intl. Conf. Wireless Internet*, 2008, pp. 1–7.

[5] J. Sahoo, E. H. K. Wu, P. K. Sahu, and M. Gerla, "BPAB: Binary partition assisted emergency broadcast protocol for vehicular *ad hoc* networks," in *Proc. 18th Int. Conf. Comput. Commun. Netw.*, 2009, pp. 1–6.

[6] C. Suthaputchakun, Z. Sun, and M. Dianati, "Trinary partition black-burst based broadcast protocol for emergency message dissemination in VANET," in *Proc. IEEE WCNC*, 2013, pp. 2244–2249.

[7] M. Fogue *et al.*, "An adaptive system based on roadmap profiling to enhance warning message dissemination in VANETs," *IEEE/ACM Trans. Networking*, vol. 21, no. 3, pp. 883–895, Jun. 2013.

[8] X. Cheng, C.-X. Wang, B. Ai, and H. Aggoune, "Envelope level crossing rate and average fade duration of nonisotropic vehicle-to-vehicle Ricean fading channels," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 62–72, Feb. 2014.

[9] X. Cheng *et al.*, "Wideband channel modeling and intercarrier interference cancellation for vehicle-to-vehicle communication systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 434–448, Sep. 2013.

[10] C. Wu, K. Kumekawa, and T. Kato, "A novel multi-hop broadcast protocol for vehicular safety applications," *J. Inf. Process.*, vol. 18, pp. 110–124, 2010.

[11] C. Wu, S. Ohzahata, and T. Kato, "VANET broadcast protocol based on fuzzy logic and lightweight retransmission mechanism," *IEICE Trans. Commun.*, vol. E95-B, no. 2, pp. 415–425, 2012.

[12] G. J. Klir, U. S. Clair, and Y. Bo, *Fuzzy Set Theory: Foundations and Applications*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1997.

[13] C. Fragouli, J. Widmer, and J.-Y. L. Boudec, "Efficient broadcasting using network coding," *IEEE/ACM Trans. Networking*, vol. 16, no. 2, pp. 450–463, Apr. 2008.

[14] S. Katti *et al.*, "XORs in the Air: Practical wireless network coding," *IEEE/ACM Trans. Netw.*, vol. 16, no. 3, pp. 497–510, Jun. 2008.
[15] C.-M. Cheng, H. T. Kung, C.-K. Lin, C.-Y. Su, and D. Vlah, "Rainbow: A wireless medium access control using network coding for multi-hop content distribution," in *Proc. IEEE MILCOM*, 2008, pp. 1–10.
[16] Q. Li, S. H. Ting, and C. K. Ho, "Joint network and channel coding for wireless networks," in *IEEE SECON Workshops*, 2009, pp. 1–6.
[17] D. Nguyen, T. Tran, T. Nguyen, and B. Bose, "Wireless broadcast using network coding," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 914–925, Feb. 2009.
[18] L. Li, R. Ramjee, M. Buddhikot, and S. Miller, "Network coding-based broadcast in mobile *ad hoc* networks," in *Proc. IEEE INFOCOM*, 2007, pp. 1739–1747.
[19] T.-X. Yu, C.-W. Yi, and S.-L. Tsao, "Rank-based network coding for content distribution in vehicular networks," *IEEE Wireless Commun. Lett.*, vol. 1, no. 4, pp. 368–371, Aug. 2012.
[20] U. Lee, J.-S. Park, J. Yeh, G. Pau, and M. Gerla, "CodeTorrent: Content distribution using network coding in VANET," in *Proc. ACM MobiShare*, 2006, pp. 1–5.
[21] U. Lee, J.-S. Park, J. Yeh, G. Pau, and M. Gerla, "VANETCODE: Network coding to enhance cooperative downloading in vehicular ad-hoc networks," in *Proc. IWCMC*, 2006, pp. 1–5.
[22] M. Li, Z. Yang, and W. Lou, "CodeOn: Cooperative popular content distribution for vehicular networks using symbol level network coding," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 223–235, Jan. 2011.
[23] J. Byers, M. Luby, M. Mitzenmacher, and A. Rege, "A digital fountain approach to reliable distribution of bulk data," in *Proc. ACM SIGCOMM*, 1998, pp. 56–67.
[24] Y. Hao, J. Tang, and Y. Cheng, "Secure cooperative data downloading in vehicular *ad hoc* networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 523–537, Sep. 2013.
[25] C. Wu, S. Ohzahata, and T. Kato, "Network coding assisted cooperative relay scheme for sender-oriented broadcast in VANETs," in *Proc. IEEE WCNC*, 2013, pp. 1387–1392.
[26] S. Li, R. Yeung, and N. Cai, "Linear network coding," *IEEE Trans. Inf. Theory*, vol. 49, no. 2, pp. 371–381, Feb. 2003.
[27] F. Bai, D. D. Stancil, and H. Krishnan, "Toward understanding characteristics of dedicated short range communications (DSRC) from a perspective of vehicular network engineers," in *Proc. ACM MobiCom*, 2010, pp. 329–340.
[28] C. Fragouli, J. Widmer, and J.-Y. Le Boudec, "Network coding: An instant primer," *ACM SIGCOM Computer Communication Review*, vol. 36, no. 1, pp. 63–68, Jan. 2006.
[29] P. Vingelmann, P. Zanaty, F. Fitzek, and H. Charaf, "Implementation of random linear network coding on OpenGL-enabled graphics cards," in *Proc. Eur. Wireless Conf.*, 2009, pp. 118–123.
[30] The Network Simulator—ns-2, Accessed on Oct. 15, 2012. [Online]. Available: http://www.isi.edu/nsnam/ns/
[31] F. Bai, N. Sadagopan, and A. Helmy, "Important: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks," in *Proc. 22nd Annu. Joint Conf. IEEE Comput. Commun. Soc.*, 2003, pp. 825–835.
[32] D. Krajzewicz, G. Hertkorn, C. Rossel, and P. Wagner, "SUMO (Simulation of Urban MObility): An open-source traffic simulation," in *Proc. 4th MESM*, 2002, pp. 183–187, SCS European Publishing House.
[33] TraNS (Traffic and Network Simulation Environment), Accessed on Oct. 15, 2012. [Online]. Available: http://trans.epfl.ch/
[34] A. Khan, S. Sadhu, and M. Yeleswarapu, "A Comparative Analysis of DSRC and 802.11 Over Vehicular Ad hoc Networks," Univ. California, Santa Barbara, CA, USA, Proj. Rep., pp. 1–8, 2009.

Celimuge Wu (M'10) received the M.E. degree from Beijing Institute of Technology, Beijing, China, in 2006 and the Ph.D. degree from The University of Electro-Communications, Tokyo, Japan, in 2010.

Since 2010 he has been an Assistant Professor with the Graduate School of Information Systems, The University of Electro-Communications. His research interests include vehicular *ad hoc* networks and networking architectures and protocols.

Satoshi Ohzahata (M'03) received the B.S., M.E., and D.E. degrees from University of Tsukuba, Tsukuba, Japan, in 1998, 2000, and 2003, respectively.

From 2003 to 2007 he was a Research Associate with the Department of Computer, Information and Communication Sciences, Tokyo University of Agriculture and Technology, Tokyo, Japan, where he was 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, Tokyo. His research interests are mobile *ad hoc* networks, the Internet architecture in mobile environments, and Internet traffic measurement.

Dr. Ohzahata is a member of the Association for Computing Machinery and the Information Processing Society of Japan.

Yusheng Ji (M'94) received the B.E., M.E., and D.E. degrees from The University of Tokyo, Tokyo, Japan, all in electrical engineering.

In 1990 she joined the National Center for Science Information Systems, Japan. She is currently a Professor with the National Institute of Informatics, Tokyo, and with The Graduate University for Advanced Studies (SOKENDAI), Kanagawa, Japan. She is also a Visiting Professor with University of Science and Technology of China, Hefei, China. Her research interests include network architecture, resource management, and performance analysis for quality of service provisioning in wired and wireless communication networks.

Prof. Ji is a member of The Institute of Electronics, Information and Communication Engineers and the Information Processing Society of Japan.

Toshihiko Kato (M'03) received the B.E., M.E., and Dr.Eng. degrees from The University of Tokyo, Tokyo, Japan, in 1978, 1980, and 1983, respectively, all in electrical engineering.

In 1983 he joined KDD and worked in the field of communication protocols of Open Systems Interconnection and Internet until 2002. From 1987 to 1988 he was a Visiting Scientist with Carnegie Mellon University, Pittsburgh, PA, USA. He is currently a Professor with the Graduate School of Information Systems, The University of Electro-Communications, Tokyo. His research interests include protocol for mobile Internet, high-speed Internet, and *ad hoc* network.