Data Dissemination with Dynamic Backbone Selection in Vehicular Ad Hoc Networks

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***Abstract*—Efficient data dissemination in Vehicular Ad hoc NETworks (VANETs) has been a challenging issue due to vehicle movements, limited wireless resources and lossy characteristics of wireless communication. In this paper, we use dynamically generated backbone vehicles to disseminate information. The proposed protocol selects the backbone vehicles by considering vehicle movement dynamics and link quality between vehicles. The proposed approach can significantly reduce the MAC layer contention time at each node while maintaining a high packet dissemination ratio. We show the effectiveness of the proposed protocol by using theoretical analysis and computer simulations.**

I. Introduction

Vehicular ad hoc networks (VANETs) have been attracting interest for their potential roles in intelligent transport systems. In VANETs, a multi-hop broadcast protocol is required for many applications including collision warning system and other value-added applications. However, due to the various vehicle densities, vehicle movement, limited bandwidth of wireless communications, it is difficult to provide a high dissemination ratio and low end-to-end delay. This is because (i) since there is no acknowledgment for the broadcast data frames at the MAC layer, the packet dissemination ratio can be very low due to the packet collisions and channel fading. (ii) there could be a large number of sender nodes contending for the channel at the same time. This incurs long wait time at the MAC layer which increases the end-to-end delay. Since a high latency can make a message out-of-date, the end-to-end delay should be seriously considered in the protocol design.

The simplest way to disseminate a message to whole network is Flooding. However, Flooding is inefficient especially when the network density is high. In order to provide a high packet dissemination ratio and low end-to-end delay, it is important to reduce the redundant broadcasts. Many protocols have been proposed to handle the issue. These protocols can be classified into two categories: (i) sender-oriented (deterministic) protocols, and (ii) receiver-oriented (non-deterministic) protocols.

In the receiver-oriented protocols, upon a packet reception, 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 schemes. There also have been some other approaches [2]–[4]. However, it is difficult for the receiver-based protocols to entirely eliminate the redundant broadcasts. In the sender-oriented protocols, each sender node specifies the relay nodes. Generally, the selection of relay nodes is based on the information collected from exchanging hello messages among neighbor nodes. Therefore, the relay node selection algorithm directly affects the protocol performance. Sahoo et al. [5] have proposed BPAB, which aims to use the most distant node in the intended direction to relay messages. However, due to the vehicle movement and channel fading, the use of the most distant node results in message losses. The research in [6] considers vehicle movement in the relay node selection. In order to provide a high reliability, retransmissions are used when a packet loss occurs at a relay node. However, the retransmissions are inefficient in terms of end-to-end delay and message overhead. The end-to-end delay of [7] needs improvement.

The sender-oriented protocols can provide a lower message overhead as compared to the receiver-oriented protocols. It is much easier to implement retransmissions for sender-oriented protocols because that the sender nodes are aware of the relay nodes. However, in all these sender-oriented protocols [5]–[7], the relay nodes are different for different broadcast data flows. This results in inefficiency in terms of MAC layer contention time, especially when the number of data flows is large.

In this paper, we propose a protocol which uses backbone vehicles to disseminate broadcast messages in VANETs. The backbone nodes are selected autonomously based on the hello message exchange among neighbor vehicles. The backbone nodes are updated periodically (with the same interval with the hello messages). For all traffic flows, the forwarder nodes are selected form the backbone nodes. Since the number of backbone nodes is limited, the number of sender nodes can be reduced efficiently. The protocol can generate a reliably connected backbone by considering the network connectivity and vehicle movement in the backbone selection algorithm. We show the advantage of the scheme using theoretical analysis and simulation results.

In section II, we give a detailed description of the proposed protocol. Next, we present theoretical analysis in section III, and present simulation results in section IV. Finally, we present our conclusions in Section V.

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II. Proposed Protocol: BBBR

A. Assumptions

We assume each node knows its position information, velocity information and antenna height. Each node transmits these information by using hello messages. The road width is considered to be negligible as compared with the radio range. All vehicles have the same transceiver and transmit with the same power. The average transmission range is assumed to be known by all vehicles. This is a plausible assumption because the average transmission range can be calculated easily from observing the packet delivery ratio from neighbors (because the neighbor position is known).

B. Protocol overview

The proposed protocol, BBBR (BackBone BRoadcast), selects backbone vehicles to relay data. As shown in Fig. 1, upon reception of a data message, a node forwards the message if itself is a backbone vehicle. The backbone vehicles are updated periodically (with the same interval as hello messages) based on the topology information acquired from the received hello messages. Backbone vehicles are selected in a distributed manner from the neighborhood. The vehicle velocity, vehicle density on the driving direction and antenna height are considered in the backbone node selection by using a fuzzy logic algorithm to combine these constraints. The backbone selection algorithm ensures the generation of a reliably connected vehicle backbone.

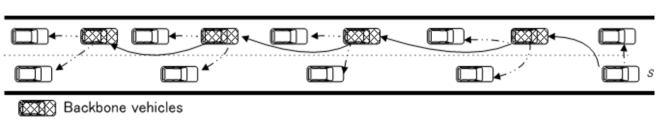

Fig. 1. Data dissemination using backbone vehicles.

C. Selection criterion for backbone vehicles

In the backbone selection, the protocol considers the vehicle velocity, the number of neighbor vehicles moving in the same direction and antenna height. The main concept of the selection algorithm is to use the relatively slow vehicles to generate the backbone. For a two-way road, the number of vehicles in one direction can be significantly larger than the other direction (for example, in the Saturday morning, many people go outside of the city). Therefore, we take in to consideration the number of vehicles driving in the same direction. When there is no significant differences between two directions, selecting a backbone vehicle from any direction is acceptable. We also consider the antenna height because that the antenna height can significantly affect the transmission quality. It is better to use the vehicles with higher antennas (bus or truck) as backbone vehicles. Since the VANET environment can be different for different road segments, it is difficult to derive a simple mathematical model. In order to get a flexible design, we use a fuzzy logic to jointly consider these metrics.

In the proposed protocol, each node sends these information (vehicle velocity, the number of neighbor vehicles moving in the same direction, and antenna height) using hello messages. For each hello interval, each node calculates a competency value (as being a backbone vehicle) for itself and each neighbor vehicle. If the node has the largest competency value in its vicinity (the details will be given later), the node announces itself as a backbone node (using the next hello message). More specifically, as shown in Fig. 2, a node calculates the competency values for other neighbors which are located in the range of $\frac{1}{4}R$ where R is the average transmission range. This ensures that in every R distance, there will be two backbone vehicles, resulting in that the backbone vehicles connect all vehicles in the network.

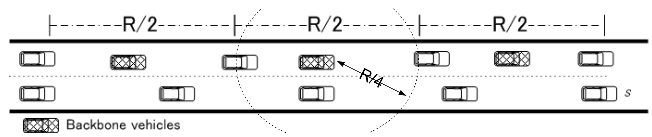

Fig. 2. Backbone selection.

D. Evaluation of each neighbor vehicle based on fuzzy logic

Each node evaluates its neighbors in close vicinity to determine which node should be the backbone node. In order to select efficient backbone vehicles, the vehicle velocity, the number of vehicles driving in the same direction, and antenna height are considered in the evaluation. We use a fuzzy logic based algorithm for the decision making.

1) Fuzzy system: Fuzzy logic [8] can process approximate data by using non-numeric linguistic variables to express the facts. Fuzzy membership functions are defined to represent the degrees of a numerical value belonging to linguistic variables (to convert the numerical value to fuzzy value). Fuzzy rules are defined to process the fuzzy value and conduct the final fuzzy value. Defuzzification is used to derive the final numerical value from the fuzzy value. Since fuzzy membership functions and fuzzy rules can be modified to satisfy a specific environment, the fuzzy logic based system is suitable for a dynamic environment.

2) Procedure: The following is the procedure for calculating a competency value for a neighbor node.

- **Calculation of multiple factors:** Calculate a Velocity Factor, Directional Traffic Density Factor and Antenna Height Factor for each neighbor vehicle that are located in the range of $\frac{1}{4}R$.
- **Fuzzification:** Use predefined linguistic variables and membership functions to convert these factors to fuzzy values.
- **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.
- **Defuzzification:** Use a predefined output membership function and defuzzification method to convert the fuzzy output value to a numerical value.

3) Calculation of multiple factors: Upon reception of a hello message from a neighbor x, node s calculates the following factors.

Velocity Factor (VF): Node s extracts the velocity of node x, $\upsilon(x)$, and calculates $VF(x)$ (the velocity factor for node x) as

$$VF(x) = \frac{|\upsilon(x)| - \min_{y \in N_s} |\upsilon(y)|}{\max_{y \in N_s} |\upsilon(y)|} \tag{1}$$

where N_s denotes the neighbor set of node s. A lower VF indicates a lower velocity.

Directional Traffic Density Factor ($DTDF$): Node x announces the number of neighbor vehicles ($c(x)$) driving to the same direction by using hello messages. $DTDF$ of node x is calculated as (2). $DTDF$ indicates the vehicle density in the same direction. A higher $DTDF$ means that the node is more suitable for being a backbone node.

$$DTDF(x) = \frac{c(x)}{\max_{y \in N_s} c(y)}. \tag{2}$$

Antenna Height Factor (AHF): Node x attaches its antenna height ($h(x)$) in the hello messages. AHF of node x is calculated as

$$AHF(x) = \frac{h(x)}{\max_{y \in N_s} h(y)}. \tag{3}$$

4) Fuzzification: The fuzzy membership functions of velocity factor, directional traffic density factor and antenna height factor are defined in Fig. 3. A node uses the velocity membership function to calculate what degree the velocity factor belongs to {Slow, Medium, Fast}. Similarly, the sender node also calculates what degree the directional traffic density factor belongs to {Heavy, Medium, Light} and what degree the antenna height factor belongs to {High, Medium, Low}.

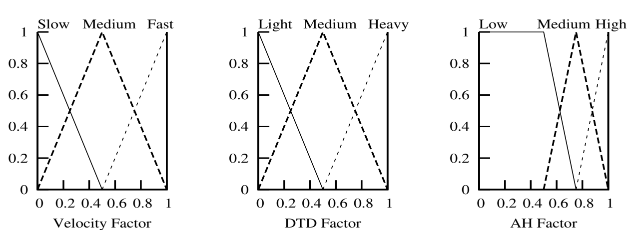

Fig. 3. Fuzzy membership functions (Left: VF, Middle: $DTDF$, Right: AHF)

5) Mapping and combination of IF/THEN rules: Based on the fuzzy values of velocity factor, directional traffic density factor and antenna height factor, a node uses the IF/THEN rules (as defined in Table I) to calculate the rank of the vehicle as being a backbone node. The linguistic variables of the rank are defined as {Perfect, Good, Acceptable, Unpreferable, Bad, VeryBad}. In Table I, Rule1 is expressed as follows.

IF *Velocity* is Slow, *Traffic density* is High, and *Antenna height* is High **THEN** *Rank* is Perfect.

Since there can be multiple rules applying at the same time, we use the Min-Max method to combine their evaluation results. In the Min-Max method, for each rule, the minimal value of the antecedent is used as the final degree. When combining different rules, the maximal value of the consequents is used (the same method as used in Ref. [7]).

TABLE I
RULE BASE

	Velocity	Traffic density	Antenna height	Rank
Rule1	Slow	Heavy	High	Perfect
Rule2	Slow	Heavy	Medium	Good
Rule3	Slow	Heavy	Low	Unpreferable
Rule4	Slow	Medium	High	Good
Rule5	Slow	Medium	Medium	Acceptable
Rule6	Slow	Medium	Low	Bad
Rule7	Slow	Light	High	Unpreferable
Rule8	Slow	Light	Medium	Bad
Rule9	Slow	Light	Low	VeryBad
Rule10	Medium	Heavy	High	Good
Rule11	Medium	Heavy	Medium	Acceptable
Rule12	Medium	Heavy	Low	Bad
Rule13	Medium	Medium	High	Acceptable
Rule14	Medium	Medium	Medium	Unpreferable
Rule15	Medium	Medium	Low	Bad
Rule16	Medium	Light	High	Bad
Rule17	Medium	Light	Medium	Bad
Rule18	Medium	Light	Low	VeryBad
Rule19	Fast	Heavy	High	Unpreferable
Rule20	Fast	Heavy	Medium	Bad
Rule21	Fast	Heavy	Low	VeryBad
Rule22	Fast	Medium	High	Bad
Rule23	Fast	Medium	Medium	Bad
Rule24	Fast	Medium	Low	VeryBad
Rule25	Fast	Light	High	Bad
Rule26	Fast	Light	Medium	VeryBad
Rule27	Fast	Light	Low	VeryBad

6) Defuzzification: The output membership function is defined as in Fig. 4. Here we use the Center of Gravity (COG) method to defuzzify the fuzzy result. For example, if 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, the consequent result function forms a shape as shown in Fig. 4. Then, we calculate the centroid of this shape. The x coordinate of the centroid is the defuzzified value which shows the competency value of the node.

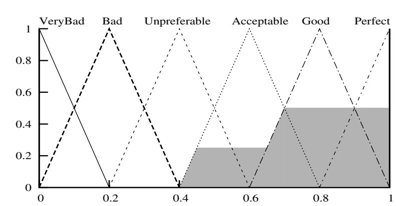

Fig. 4. Output membership function.

E. Advantages of the proposed protocol

Since the backbone vehicles are selected autonomously, the sender node does not need to specify the relay nodes. The proposed protocol generates the backbone by using only hello messages, and disseminates broadcast messages using backbone vehicles, resulting in a low message overhead. For each hello interval, the backbone vehicles are fixed. The fixed backbone can limit the number of sender nodes contending for the channel access, therefore can significantly improve the MAC layer channel usage efficiency. In the proposed, any two backbone nodes are located near than R. The backbone selection algorithm also considers vehicle movement and antenna height. This ensures that the protocol can generate a reliably connected backbones. Therefore, the protocol can provide a high reliability, low overhead and low delay.

III. Theoretical analysis

A. Analytical model

We assume the sensing range is the same to the transmission range R. If multiple nodes, which are located in each other's sensing range, transmit at the same time, collisions occur. This is true because we are considering broadcast applications of which aim is to disseminate data to all nodes in the network. Selecting the same backoff time is considered to be the main reason for the collisions. We do not consider the effect of DIFS on the collisions.

B. The number of backbone nodes in the sensing range

The protocol ensures that there would be at least one backbone node for each road segment with the length of $\frac{1}{2}R$. Therefore, the distance between any two backbone nodes are smaller than R. Since a node is selected as a backbone node only when the node is the local maximum (in the range of $\frac{1}{4}R$), there will be only one node in each $\frac{1}{4}R$ distance at maximum. This means that there is the upper bound for the number of backbone vehicles. For each road segment with the length of R, the upper bound is 4. In most cases, the number of backbone nodes in the sensing range is 3. Therefore, the protocol can significantly reduce the number of sender nodes especially in a high-density network.

C. MAC layer contention time

In the MAC layer specification of IEEE 802.11 standard, the backoff time is a random number which is drawn from a uniform distribution over the interval [0,CW] where CW is the current contention window. The CW is a value between CW_{min} and CW_{max}. According to the IEEE 802.11p, CW_{min} is 15 and CW_{max} is 1023. For a broadcast data, each node selects a random backoff time and decrements the backoff interval counter while the medium is idle. Since there is no collision detection at the sender node (no ACK), CW does not change for the broadcast data transmissions.

When N is number of sender nodes, the possibility of at least one node selecting a given backoff time BO (which is drawn from [0,CW]) is

$$\Theta(N) = 1-(1-\frac{1}{\mathrm{CW}+1})^N. \tag{4}$$

We can derive the probability of at least one node transmitting at slot No. 0 as

$$\Delta(0,N) = \Theta(N). \tag{5}$$

However, for each node, there are two possible ways to transmit at the slot No. 1: (i) the node selects the backoff time 1 (slot No. 1) (ii) the node selects backoff time 0 and successfully sends a MPDU (or MMPDU), and then selects backoff time 1 for the next MPDU (or MMPDU). Therefore, the probability of at least one node transmitting at slot No. 1 is

$$\Delta(1,N) = \Theta(N) + (1-\Theta(N))\,\frac{\Theta(N)}{\mathrm{CW}+1}. \tag{6}$$

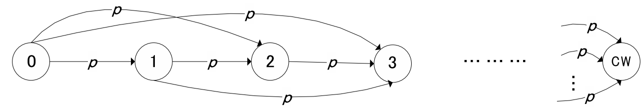

Fig. 5. Backoff time transition.

Fig. 5 shows the transition probability of transmissions at each time slot. In the figure, each circle (with a number) shows a time slot. Start point and end point of each arrow denote the time slots of the previous transmission and the next transmission respectively. For example, the arrow "0→2" shows that a node could transmit at the time slot No. 0 and then transmit at the time slot No. 2. The probability of transmitting at the time slot No. 2 after transmitting at the slot No. 0 is p. Since the backoff time is uniformly distributed, p can be calculated as

$$p = \frac{1}{\mathrm{CW}+1}. \tag{7}$$

Based on (5) and Fig. 5, we can calculate $\Delta(x,N)$ as

$$\begin{aligned}\Delta(2,N) &= \Theta(N) + (1-\Theta(N))\left((p^2+p+p)\cdot\Theta(N)\right)\\ &\cdots\cdots\\ \Delta(x,N) &= \Theta(N) + (1-\Theta(N))\left(\sum_{i=1}^{x}\binom{x}{i}p^i\cdot\Theta(N)\right)\end{aligned} \tag{8}$$

Each node has to pause the backoff interval counter while the medium is busy. Each transmitter node has to restart the backoff algorithm after a transmission of MPDU (or MMPDU). When T_{data} is the time required for sending one MPDU, channel busy incurred delay for the time slot BO (when the node selects backoff time BO) can be calculated as

$$\tau(BO,N) = \sum_{j=0}^{BO-1}\Delta(j,N)\cdot T_{data} \tag{9}$$

Since the backoff time is a uniform distribution over the interval [0,CW], the average backoff time is $\frac{\mathrm{CW}+1}{2}$. Therefore, the corresponding channel busy incurred delay is

$$\begin{aligned}\tau(\frac{\mathrm{CW}+1}{2},N) &= \sum_{j=0}^{\frac{\mathrm{CW}+1}{2}-1}\Delta(j,N)\cdot T_{data}\\ &= \Theta(N)\cdot\frac{\mathrm{CW}+1}{2}\cdot T_{data} +\\ (1-\Theta(N))&\left(\sum_{j=1}^{\frac{\mathrm{CW}+1}{2}-1}\sum_{i=1}^{j}\binom{j}{i}p^i\right)\cdot\Theta(N)\cdot T_{data}\end{aligned} \tag{10}$$

The total MAC contention time can be calculated as

$$\Lambda(\frac{\mathrm{CW}+1}{2}) = \tau(\frac{\mathrm{CW}+1}{2}) + \frac{\mathrm{CW}+1}{2} \tag{11}$$

Fig. 6 shows the channel busy time for various number of nodes in the sensing range. In the traditional broadcast approach, the relay nodes are not fixed, therefore the number of sender nodes can be very large. The number of sender nodes has a significant effect on the channel busy time which is the dominant factor of MAC contention time (see (11)). As shown in the figure, the proposed protocol can reduce the delay by using a small number of sender (backbone) nodes.

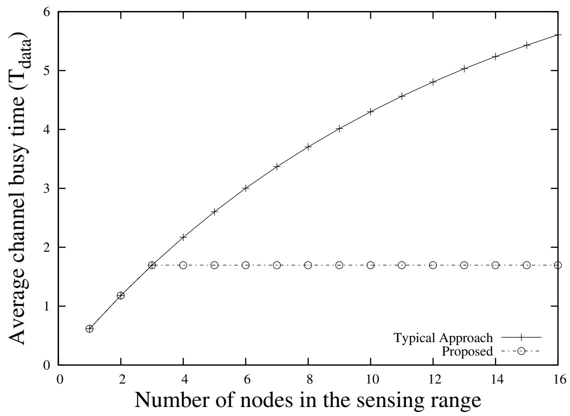

Fig. 6. Channel busy time for various number of nodes in the sensing range.

D. Probability of collisions

If multiple nodes choose the same backoff time, collisions occur. As we mentioned before, the probability of a node choosing a given backoff time is $\frac{1}{\mathrm{CW}+1}$. If node z selects BO as the backoff time, node z only can successfully transmit when all other $(N-1)$ nodes select different backoff time. As shown in (8), the probability of any other nodes choosing the same backoff is $\Delta(BO, N-1)$. Therefore, we can calculate the expected collision probability as

$$\zeta(N) = \frac{1}{\mathrm{CW}+1} \sum_{k=0}^{\mathrm{CW}} \Delta(k, N-1) \tag{12}$$

Based on (12), Fig. 6 shows the collision probability for various number of nodes in the sensing range. Due to the backbone based forwarding mechanism, the proposed protocol can control the collision probability at a very low level.

IV. Simulation Results

We used ns-2.34 [9] to conduct simulations in Freeway scenarios [10]. Simulation environment are shown in Table II. The maximum allowable vehicle velocity was 40m/s. Two neighboring source nodes generated broadcast traffics. This is to simulate a condition of two collided vehicles send data messages at the same time. Nakagami propagation model was used to simulate the channel fading (see Table III). We used these parameter values because they model a realistic wireless channel of VANETs [11]. In the simulation, 10% of vehicles were with higher antennas. The links involving the higher antenna vehicles were set to provide 10% higher reception probability when other parameters are the same.

The proposed protocol was compared with Flooding, Weighted p-persistence [1] and Enhanced MPR Broadcast

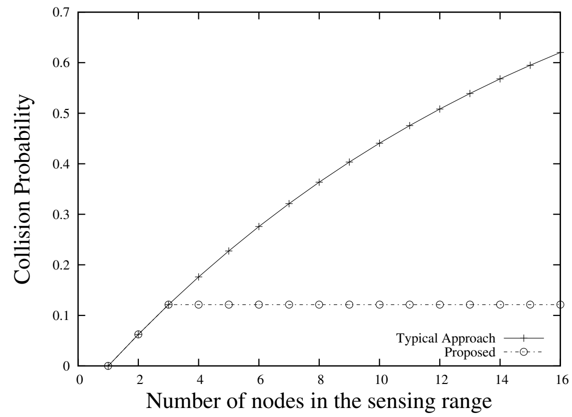

Fig. 7. Collision probability for various number of nodes in the sensing range.

[6]. In the Weighted p-persistence scheme, a receiver node first calculates a broadcast probability according to the distance from the sender node and rebroadcasts the packet with this probability. In the Enhanced MPR Broadcast, a receiver rebroadcasts the packet only if it is itself specified as a relay node. Each node retransmits a packet when the node does not receive the corresponding ACK from any intended receivers in a predefined time interval. The maximum number of retransmissions was set to be 4. In the following simulation results, the error bars indicate the 95% confidence intervals.

TABLE II
Simulation Environment

Topology	2000 m, 4 lanes (two lanes in each direction)
Number of nodes	100 to 600
Mobility generation	Ref. [10]
Number of sources	2
Number of packets	50 packets at each source
Packet size	512 bytes
Broadcast data rate	10 packet per sec
MAC	IEEE 802.11 MAC (2 Mbps)
Propagation model	Nakagami Model
Simulation time	150 s

TABLE III
Parameters of Nakagami Model

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

A. Number of messages

Fig. 8 shows the number of messages per data packet for various numbers of nodes. This performance metric is calculated as the number of messages generated (including both ACK messages and data messages transmitted by all nodes in the network) divided by the number of data packets generated by the source nodes. The proposed protocol (BBBR) can significantly reduce the number by using backbone nodes to disseminate data packets. The Flooding and Weighted p-persistence scheme incur a large number redundant transmissions. The Enhanced MPR Broadcast shows the largest number of broadcasts due to the ACK messages and retransmissions.

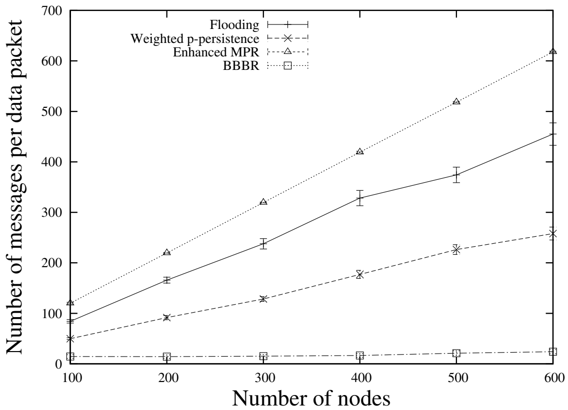

Fig. 8. Number of messages per data packet for various numbers of nodes.

B. Packet dissemination ratio

Fig. 10 shows the packet dissemination ratio for various numbers of nodes. BBBR shows the best performance due to the efficient backbone node selection algorithm which considers link quality and vehicle mobility. Flooding and Weighted p-persistence scheme are inefficient due to the packet collisions incurred from the redundant transmissions. The retransmissions contribute to the better performance of Enhanced MPR Broadcast as compared with Flooding and Weighted p-persistence scheme.

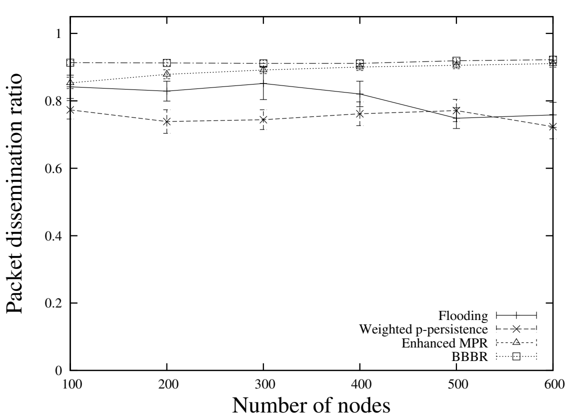

Fig. 9. Packet dissemination ratio for various numbers of nodes.

C. End-to-end delay

Fig. 10 shows the average end-to-end delay for various numbers of nodes. Due to the backbone based forwarding algorithm, BBBR can significantly reduce MAC layer contention time at each node, resulting in the lowest end-to-end delay. The increase of the delay (as the node density increases) is due to the increase of the number of hello messages.

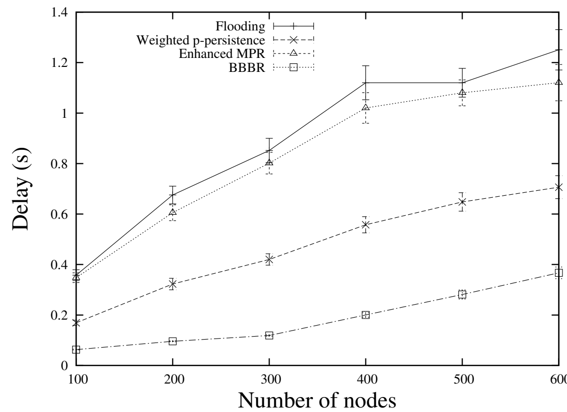

Fig. 10. End-to-end delay for various numbers of nodes.

V. Conclusions

We proposed BBBR, a backbone based broadcast protocol for VANETs. In BBBR, data packets are delivered by the backbone nodes. The backbone vehicles are updated once for each hello interval. The protocol chooses backbone vehicles by considering vehicle mobility, the number of neighbor vehicles moving in the same direction and antenna height. The theoretical analysis and simulation results showed the advantage of the proposed protocol over existing solutions.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 25730053.

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