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Performance Evaluation of Probabilistic Relay in Ad Hoc On-demand Distance Vector and Ad Hoc On-demand Multipath Distance Vector under Highly Dynamic Environments

[1,2]Radityo Anggoro, [1]Teruaki Kitasuka,
[1]Ryoji Nakamura and [1]Masayoshi Aritsugi

[1]Graduate School of Science and Technology,
Kumamoto University, Kumamoto, Japan
[2]Department of Informatics, Faculty of Information Technology,
Institute Teknologi Sepuluh Nopember Surabaya, Indonesia

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ABSTRACT

Vehicular Ad hoc Networks (VANETs) are a specific class of Mobile Ad hoc Networks (MANETs). Since vehicles tend to move in a high speed, the network topology is rapidly changed. Thus vehicle's connectivity problem is one of the interesting issues in VANETs. Ad hoc On-demand Multipath Distance Vector (AOMDV) is an extended version of ad hoc on-demand distance vector (AODV). AOMDV is designed to overcome a connectivity problem due to highly dynamic network topology. It provides multipath for data packets delivery from the source to the destination. However, AOMDV's multipath establishment and maintenance generate more control packets than those of AODV's unipath. Meanwhile, both protocols degrade their performance when the vehicle speed is increasing. Thus in this study, we added probabilistic relay, which enables adjacent vehicles to probabilistically relay unsuccessful data packet transmission into IEEE 802.11 as a MAC standard model and proposed AODV with Probabilistic Relay (AODV-PR) and AOMDV with Probabilistic Relay (AOMDV-PR). Based on our simulation results, the addition of probabilistic relay clearly helps those protocols to improve their performances especially in packet delivery ratio under highly dynamic environments. Probabilistic relay adds the number of generated beacon messages, but does not produce any additional routing messages. We evaluate those protocol performances based on several metrics such as packet delivery ratio, routing overhead, average delivery delay, hop count and number of relays under variation of vehicle speed and beacon interval. We show that beacon interval has a huge influence in the performance of AODV-PR and AOMDV-PR especially for their routing overhead.

Keywords: IEEE 802.11, Probabilistic Relay, Routing Protocols, VANETs

1. INTRODUCTION

1.1. Backgrounds

Vehicular Ad-hoc Networks (VANETs) are an extended class of Mobile Ad-hoc Networks (MANETs). As a class of wireless ad-hoc networks, their nodes are self-organized and distributed. Apart from their similarities, highly dynamic topology and vehicle mobility are the main differences. Those unique characteristics turn the setup of routing protocols suitable for VANET environments into an enormous challenge.

Many routing protocols have been proposed to address routing issues in VANETs. Basically, they are divided based on transmission technique into three types: Unicast, broadcast and multicast routing protocols. Unicast is transmitting the packets to a single destination, while broadcast is transmitting to all possible

Corresponding Author: Radityo Anggoro, Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan

destinations. On the other hand, multicast is transmitting the packets to a particular group of destinations.

Unicast protocol can be categorized into two main types: topology-based protocols such as Ad hoc On-Demand Distance Vector (AODV) (Perkins *et al*., 2003), Ad hoc on-demand multipath distance vector (AOMDV) (Marina and Das, 2006), Dynamic Source Routing (DSR) (Johnson and Maltz, 1996) and Optimized Link State Routing Protocol (OLSR) (Clausen *et al*., 2003); and position-based ones such as Greedy Perimeter Stateless Routing (GPSR) (Karp and Kung, 2000), Vehicle-Assisted Data Delivery (VADD) (Zhao and Cao, 2006) and Geographical Opportunistic (GeOpps) (Leontiadis and Mascolo, 2007) and Connectivity-Aware Routing (CAR) (Naumoy and Gross, 2007). Among those unicast protocols, there are several protocols that are designed specifically to adapt to VANET environments such as CAR, VADD and GeOpps. However, those protocols focus on the modification of their network layer to solve connectivity problem.

Meanwhile, our work only focuses on MAC layer to create a certain retransmission control without changing routing decision of the protocols. In a certain situation when the vehicle in the middle of transmitting the data packets, high speed movement of vehicle may cause its predetermined next hop is out of range, thus the transmission is failed. Originally, this situation forces the protocol to alter its routing decision such as re-execute route discovery process to fix the broken link. However in this study, we try to utilize surrounding environment by allowing adjacent vehicles to probabilistically relay unsuccessful transmission. We restrict our performance evaluation only on unicast protocols, AODV and AOMDV combined with probabilistic relay.

1.2. Related Work

Due to highly dynamic topology, connectivity problem becomes one of the interesting issues in VANETs. Balasubramanian *et al*. (2008) explored sender diversity to improve the connectivity between a static basestation and a moving vehicle. It occupies several static basestations to communicate with a vehicle. A basestation, called an anchor, sends and receives packets to and from the vehicle. Auxiliary basestations probabilistically relay undelivered packets to the anchor or the vehicle. The relaying probability is calculated independently by other auxiliary basestations, based on the reception probability recorded through the exchange of beacon messages. Based on that work, we try to add probabilistic relay (Balasubramanian *et al*., 2008) into routing protocols for vehicle-to-vehicle communication and evaluate their performance under VANETs.

There are many performance evaluations of routing protocols which have been published. Santoso and Kang (2012) evaluate AODV, DSDV and OLSR for a safety application in VANETs. In order to provide important information for safety, minimizing packet delivery delay has the priority for this application. Thus, they focus on maximum packet delay as one of their metrics in highway traffic scenarios. Meanwhile in this study, our targeted applications are not limited to the safety application. Our targeted environment is for city scenarios which are rich of traffic lights, vehicles and intersections that can vary the movement of vehicles, not as constant as on highway.

Nagaraj and Dhamal (2012) study performance comparison of AODV, AOMDV, OLSR, DSR and GSR under VANET environments. It shows that AODV and AOMDV significantly outperformed the others in packet delivery ratio. However, the trade-off is in their delivery delay. Since those two protocols need to setup route discovery before they start to send the data packets, they put additional delay. Meanwhile, DSR, OLSR and GSR produce average results for both metrics. However, they still cannot produce an acceptable delivery ratio under VANET scenario.

Those works (Santoso and Kang, 2012; Nagaraj and Dhamal, 2012) basically evaluate the performance of original MANETs protocols into VANET scenarios and study their trade-off for each of their performance metrics. However in this study, our focus is on improving the performance of selected MANETs protocols by adding probabilistic relay in their MAC layer. Thus, they can utilize the neighbourhood for dealing with connectivity issue in highly dynamic environments of VANETs. We deliberately focused our evaluation on AODV and AOMDV as reactive protocols. It has been proved from our previous work (Anggoro *et al*., 2011) that proactive and position based protocols suffer their performance due to high maintenance overhead than reactive protocols. We extended our work (Anggoro *et al*., 2012) on evaluating AODV and AOMDV combined with probabilistic relay for vehicle-to-vehicle communication under highly dynamic environments. We add probabilistic relay into AODV and AOMDV then compare their performances. We called those modified protocols AODV-PR and AOMDV-PR. Our simulation shows that the addition of probabilistic relay into the routing protocols clearly improved their performances.

1.3. Paper Organization

The rest of this study is organized as follows: In Section 2, we describe AODV, AOMDV and probabilistic relay. Section 3 presents evaluation settings and parameters for evaluating the protocols under realistic VANET scenarios and discusses the simulation results. Finally, in Section 4, we give our conclusion and future work.

2. ROUTING PROTOCOLS and PROBABILISTIC RELAY

2.1. Ad Hoc On-demand Distance Vector

Ad hoc On-demand Distance Vector (AODV) routing protocol (Perkins *et al*., 2003) is one kind of reactive protocols. AODV creates a route only when the source node has a data packet to be sent. This on-demand behavior produces lower routing overhead than proactive protocols. When the route to the destination is needed, it starts route discovery process by disseminating a Route Request (RREQ) message through the network. If a node receives a RREQ which has not been seen before and does not know any route to the destination, it marks a reverse path to the sender and rebroadcasts the RREQ through the network. If the node knows about a route to the destination or the node is the destination itself, it sends a unicast transmission of Route Reply (RREP) message back to the source through the reverse path that already established. After the source receives the RREP, it finally has a route to send data packets to the destination.

Figure 1 shows AODV route establishment. When node S has to send a data packet to node D, node S will broadcast RREQ through the network. When node D receives the broadcasted RREQ, it will respond by sending unicast transmission of RREP back to node S through the established reverse path D-C-B-A-S. After node S receives RREP, it learns that node A is the next hop to reach node D. Thus, the complete route from node S to node D is S-A-B-C-D. After the route from the source to the destination is created, the route needs to be maintained properly. Due to highly dynamic topology, link breakage occurs frequently. A node detects disconnected link from the periodic exchange of Hello messages. If a disconnected link is detected, the node broadcasts a Route Error (RERR) message that contains a list of unreachable nodes and their information. If the disconnected link is in an active route, the node tries to repair it locally by sending RREQ to find a new route to the destination.

2.2. Ad hoc On-Demand Multipath Distance Vector

Ad hoc on-demand multipath distance vector (AOMDV) routing protocol (Marina and Das, 2006) is an extended version of AODV. AOMDV provides multiple paths to reach the destination while AODV only has a unipath to the destination. Despite of their difference, both protocols share the same behavior in several things such as reactive route discovery mechanism and route maintenance. AOMDV also has similar kind of routing packets such as RREQ, RREP, RERR and Hello messages. However, AOMDV in particular has extra RREP and RERR for multipath discovery and maintenance along with few extra fields in routing control packets. Thus it costs more routing overhead than AODV. AOMDV establishes the route to the destination through route discovery process as basically the same as AODV does. However, instead of responding to one RREQ, the destination will respond to several numbers of RREQs by sending unicast transmission of multiple RREPs back to the source. Thus it creates the multipath between the source and the destination. The challenge of how to ensure the loop free and disjoint path is the issue that needs to be considered in AOMDV.

An example of loop possibility in AOMDV is illustrated in **Fig. 2**. Assume that node S has two established routes to reach node D through S-G-E-C-F-D by five hops and one hop through S-D. If S later advertises the information of its route S-D to node A, later on node S will learn that it has four hops to reach node D through node B. Since node S cannot tell whether node B is its downstream or upstream, a loop will be created through S-B-A-S-D. That situation occurs because node S advertises a shorter route than the one already advertised. In order to make sure that the multipath is loop free, AOMDV sets up two rules for the node; First, for the same destination sequence numbers, nodes never advertise a route shorter than one already advertised. Second, nodes never accept a route longer than one already advertised

Meanwhile, AOMDV uses the term of disjoint path as link disjoint instead of node disjoint as in the graph theory. Thus, the illustration of disjoint path is shown in **Fig. 3**. Let assume that node S has the first two paths to reach node D through S-A-C-E-D and S-B-C-F-D. Node S cannot create additional paths such as S-A-C-F-D and S-B-C-E-D because those links are not disjoint with the first two paths (S-A-C-E-D and S-B-C-F-D). In order to ensure disjoint path, the node has to maintain the last hop information as an addition to next hop information carried by RREQ and RREP at route discovery process. The route from the source to the destination is disjoint path if they have unique next hop as well as unique last hop. The last hop of a path from the source to the destination refers to the node immediately preceding the destination on the path.

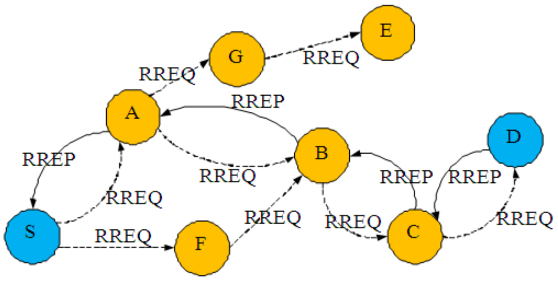


Fig. 1. Ad hoc On-demand Distance Vector

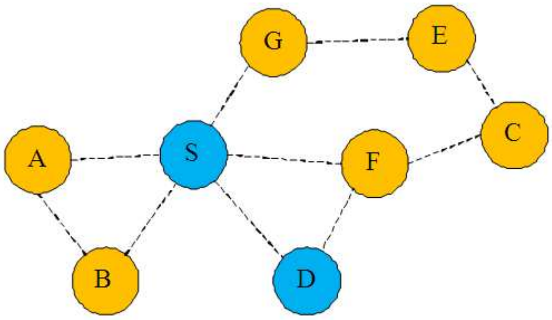


Fig. 2. Loop free of AOMDV

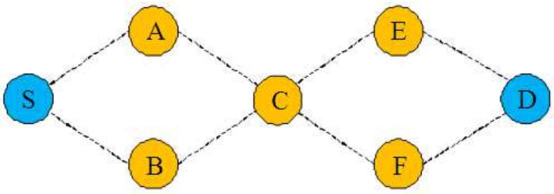


Fig. 3. Disjoint path of AOMDV

Table 1. Reception probability

$P(S)$	0.75
$P(S_{i+1}\|\neg S_i)$	0.24
$P(B_{i+1}\|\neg S_i)$	0.57
$P(B)$	0.67
$P(B_{i+1}\|\neg B_i)$	0.18
$P(S_{i+1}\|\neg B_i)$	0.62

In **Fig. 3** when node C received two RREP originated by node D, it confirmed that those two paths are disjoint. Each path to node D has different last hop which is node E or F. Thus node C incrementally creates two link disjoint paths to node D via nodes E or F. Suppose node C advertises the paths to node D via nodes E and F to nodes A and B respectively. Note that each path advertisement includes the last hop of the path. Then paths from nodes A and B to node D are link disjoint as each of them has distinct last hop (node E or F). Thus, S can incrementally form two link disjoint paths to D via node A and B. AOMDV follows those two rules in order to ensure the loop free and path disjoint for its multipath.

2.3. The Concept of Probabilistic Relay

The idea of probabilistic relay (Balasubramanian *et al*., 2008) enables adjacent basestations to relay an undelivered packet instead of waiting for retransmission. They deploy probabilistic relay into static basestations to communicate with moving vehicles. The main purpose of probabilistic relay is to provide a reinforcement node to relay a data packet instead of waiting for retransmission when data packet transmission is unsuccessful. The initial work explored sender diversity, which can effectively tackle losses in vehicular environments. They (Balasubramanian *et al*., 2008) also examined the nature of lost packets, as shown in **Table 1**. They calculated the reception probability of a data packet from basestation S and basestation B to a moving vehicle via periodic reception of beacon messages among them. For example, $P(S)$ is the unconditional reception probability from basestation S while $P(B)$ is that from basestation B. $P(S_{i+1}|\neg S_i)$ is the conditional reception probability of the (i+1)-th packet from basestation S, given that the i-th packet from basestation S is lost.

As shown in **Table 1**, $P(B_{i+1}|\neg S_i)$ is larger than $P(S_{i+1}|\neg S_i)$. Also, the same comparison is true for $P(S_{i+1}|\neg B_i)$ and $P(B_{i+1}|\neg B_i)$. Based on these probabilities, they concluded that retransmission of undelivered packets by the same source is not a better option than another node that can help to retransmit the data packet.

Multiple adjacent nodes named $A_1,\ldots, A_k$ $(k>1)$ can exist around sender S and receiver D. To avoid collisions among adjacent nodes, each adjacent node probabilistically retransmits the packet. The relaying probability r_i of node A_i is calculated in node A_i locally. To calculate the probability r_i locally, every node transmits beacons periodically with the reception probability of other neighbours. Each node calculates the reception probability from another node to itself by using the number of beacons received for a particular time interval divided by the number of beacons sent for the interval. These incoming reception probabilities are maintained as exponential averages $(\alpha = 0.5)$ over the per-second beacon reception ratio. The challenge in computing the relaying probability is to balance the trade-off between too few and too many relayed transmissions. If it is too few, the performance will be degraded, so that no diversity exists. If it is too many, it will increase the collisions of the retransmitted packet. That condition needs to be considered when determined the formula for relaying probability calculation. Adjacent nodes, which have better connections to the destination, are preferred for the relay. When each adjacent node A_i hears a data packet but not an acknowledgment yet, node A_i uses its locally computed relaying probability r_i to decide whether to relay the data packet. The following formulas (Balasubramanian *et al*., 2008) describe how to calculate the relaying probability r_i.

$$\sum_{i=1}^{k} c_i r_i = 1 \tag{1}$$

where, c_i, defined in Equation 2, is the probability that adjacent node A_i hears the packet but does not hear the acknowledgment. From Equation 1, the expected number of packets relayed across all adjacent nodes, $A_1,\ldots, A_k$, is equal to 1:

$$c_i P_{SA_i}(1 - P_{SD}P_{DA_i}) \tag{2}$$

where, P_{xy} ($x, y \in \{S, D, A_1,\ldots, A_k\}$) is the probability that node y receives the packet from node x. Then, ($1 - P_{SD}P_{DAi}\}$) is the probability that A_i does not hear an acknowledgment from node D. To satisfy Equation 1, r_i is calculated by $r_i = r \cdot P_{AiD}$, where r is defined in Equation 3:

$$r = \frac{1}{\sum_{j=1}^{k} P_{SA_j}(1 - P_{SD}P_{DA_j})P_{A_jD}} \tag{3}$$

2.4. Probabilistic Relay for Vehicle-to-Vehicle Communications

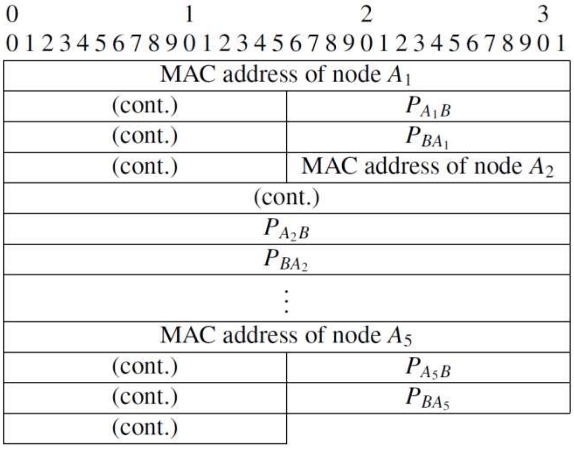
In this study, we extend their work (Balasubramanian *et al*., 2008) by deploying probabilistic relay for vehicle-to-vehicle communication. We add probabilistic relay into routing protocols under VANET environments. In our implementation, the addition of probabilistic relay into IEEE 802.11 necessitates one extra table. This table records reception probabilities list (P_{xy}). Probability $P_{xy}(t)$ which is P_{xy} at time t is calculated in Equation 4:

$$P_{ij}(t) = \alpha \frac{N_{received}}{N_{sent}} + (1-\alpha)P_{ij}(t-1) \tag{4}$$

where, $N_{received}$ is the number of beacons received and N_{sent} is the number of beacons sent for an interval, $P_{xy}(t-1)$ is the previous reception probability at time (t-1) and $\alpha = 0.5$. In their beacon messages, every node also includes several related information from their reception probability table. Consequently, every node can completely update its own reception probability table. **Figure 4** shows the format of the reception probability included in a beacon message. When a vehicle generates a beacon, it adds reception probability information to the beacon.

Figure 4 is an example of the beacon message format transmitted by node B, which includes the reception probability of five adjacent nodes: $A_1,\ldots,A_5$. The reception probability P_{xy} is calculated on the receiver side node y. Then the vehicle can insert probability information of the top five receptions into the beacons ordered by the P_{xy} column from the rows in its reception probability table, as shown in **Table 2**, an example of reception probability table of vehicle B. The addition of probabilistic relay into routing protocols adds an extra table and field in the beacon message header.

Balasubramanian *et al*. (2008) proved about the nature of lost packets which confirmed that retransmission of undelivered packet by the same source is not a better option than another basestation that can help to retransmit the packet. **Figure 5** shows the situation in which probabilistic relay applies for vehicle-to-vehicle communication. $P(S_{i+1}|\neg S_i)$ is the conditional reception probability of the (i+1)-th packet from vehicle S, given that the transmitted i-th packet from vehicle S to vehicle D is lost. Meanwhile, $P(A_{i+1}|\neg S_i)$ or $P(B_{i+1}|\neg S_i)$ is the conditional reception probability of the (i+1)-th packet to vehicle D from vehicle A or B, after the transmission of i-th packet from vehicle S is failed. As it already observed (Balasubramanian *et al*., 2008), $P(S_{i+1}|\neg S_i)$ is smaller than $P(A_{i+1}|\neg S_i)$ or $P(B_{i+1}|\neg S_i)$. Thus, having adjacent vehicle relays unsuccessful packet transmission is a better way than waiting for retransmission.



0 1 2 3

0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

MAC address of node A_1	
(cont.)	P_{A_1B}
(cont.)	P_{BA_1}
(cont.)	MAC address of node A_2
(cont.)	
P_{A_2B}	
P_{BA_2}	
⋮	
MAC address of node A_5	
(cont.)	P_{A_5B}
(cont.)	P_{BA_5}
(cont.)	

Fig. 4. Reception probability in vehicle B's beacon

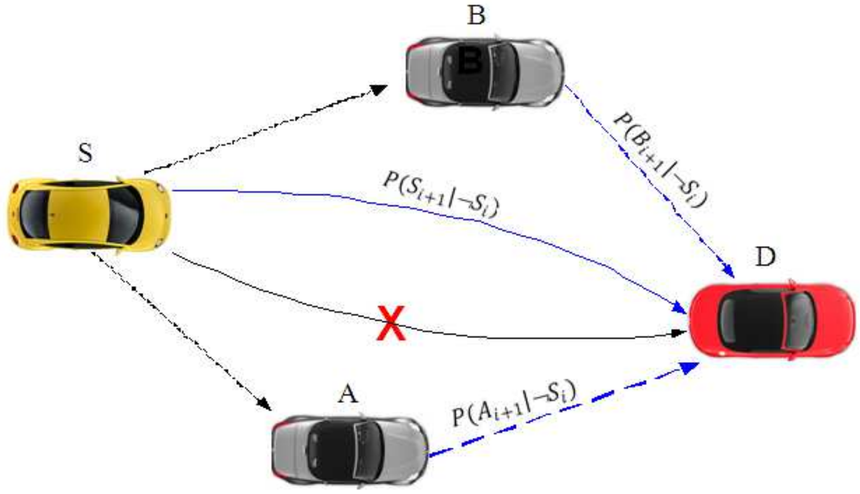


Fig. 5. Probabilistic Relay for Vehicle Communication

Table 2. Reception probability table of vehicle B

Vehicle x	Vehicle y	P_{xy}	P_{yx}
B	S	0.6	0.8
B	A	0.2	0.6
B	D	0.3	0.3
S	A	0.4	0.4
S	D	0.5	0.2
A	D	0.7	0.5

In the example of **Fig. 5**, when the transmission from vehicle S to vehicle D is dropped, vehicle S will execute retransmission until maximum number of retries as in WLAN standard IEEE 802.11. However, probabilistic relay allows vehicle A or B, which overhears the transmitted packet by vehicle S and hears that no acknowledgment was sent by node D, to relay the undelivered packet to vehicle D. However, if the relay transmission by those adjacent vehicles is failed vehicle S will retransmit it again.

Vehicles A and B have potential to relay unsuccessful transmission from vehicle S to vehicle D. The entries of **Table 2** are updated by receiving each beacon message. In this example, vehicle B directly calculates P_{SB}, P_{AB} and P_{DB} from the receiving beacon by Equation 4. To completely update the table, vehicle B also updates its corresponding column of P_{BS}, P_{SA}, P_{AS}, P_{SD} and P_{DS}, which are retrieved from the beacon of vehicle S. The entries of P_{BA}, P_{AD} and P_{DA} are obtained from the received beacon of vehicle A while P_{BD} and P_{SD} are retrieved from the received beacon of vehicle D. Thus, r_b can be calculated as $r_b = r \cdot P_{BD}$. Vehicle B decided to relay the packet if r_b is greater than or equal to its own generated random number using uniform distribution function. Otherwise, it keeps silent.

2.5. Probabilistic Relay Addition to the Routing Protocols

The addition of probabilistic relay does not change AODV and AOMDV behavior. It only changes on the way the link layer deals with undelivered unicast transmission. It does not respond to broadcasted transmission. For example in AODV and AOMDV, only unicasted data packets, RREP and RERR are probabilistically relayed while broadcasted Hello, RREQ and RERR are never relayed.

Since probabilistic relay tends to avoid retransmission and mainly depends on adjacent vehicles to relay unsuccessful transmission, the retransmission timer in the link layer needs to be extended. Thus, adjacent vehicles have a chance to hear unsuccessful transmission and then relay that unsuccessful transmission. **Figure 6** shows the back-off algorithm after the addition of probabilistic relay. S, D and A stand for source, destination and adjacent vehicles. At t_0 vehicle S sends a data packet to vehicle D. In the original form, vehicle S starts its retransmission timer for $(t_1\text{-}t_0)$ seconds. However, in order to give vehicle A a chance as its neighbor to react for unsuccessful transmission, vehicle S needs to extend its retransmission timer for $(t_2\text{-}t_0)$ seconds. Thus, the relaying transmission by vehicle A can be confirmed by the arriving of ACK before t_2.

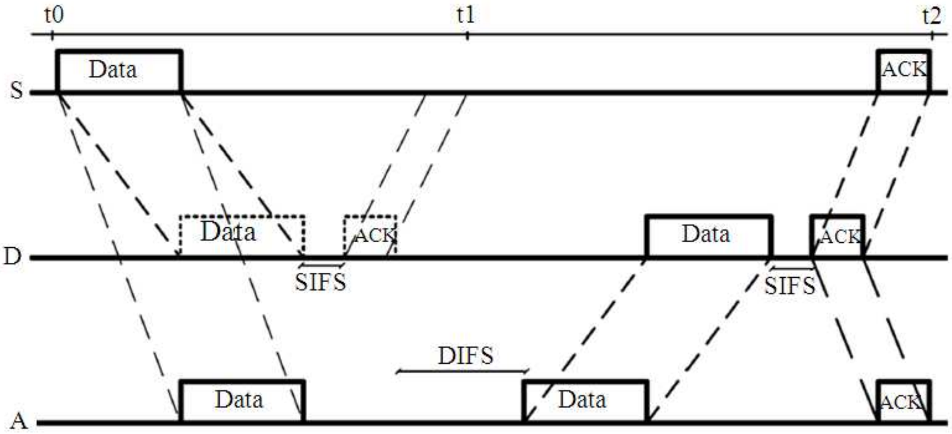
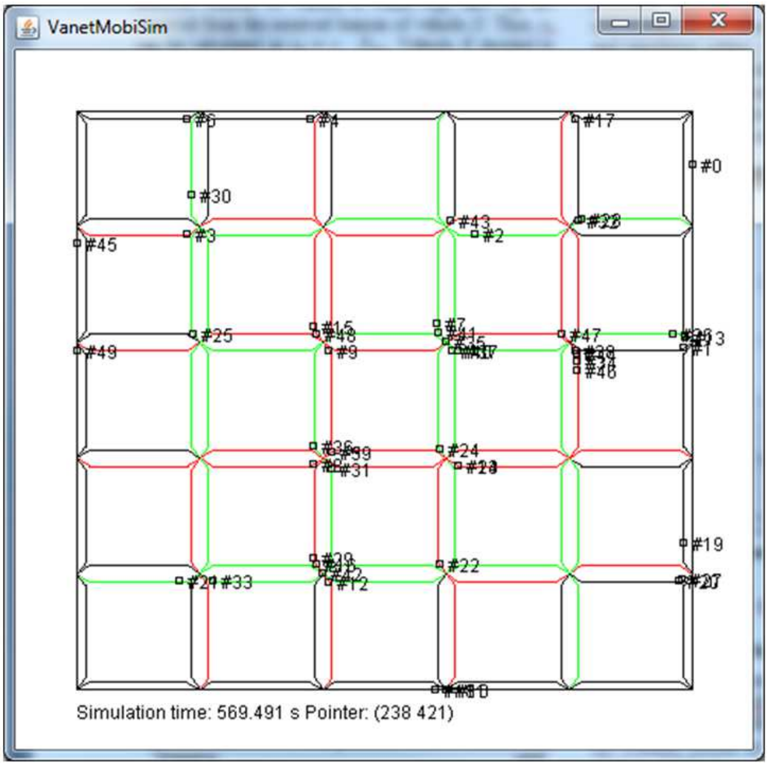


Fig. 6. Back-off algorithm for probabilistic relay protocol



Simulation time: 569.491 s Pointer: (238 421)

Fig. 7. VanetMobiSim Map

3. PERFORMANCE EVALUATION

In this study, we compare AODV and AOMDV with and without probabilistic relay through network simulator ns-2.34. We divide this section into four subsections. In subsection 3.1, we describe our parameter and simulation setting. Subsection 3.2 shows preliminary evaluation of probabilistic relay under static network environments. Subsection 3.3 describes the results of our simulation for a single connection while subsection 3.4 shows the simulation results for multiple connections.

3.1. Evaluation Setting and Metrics

For our realistic mobility scenarios, we generate our scenario using VanetMobiSim (Harri *et al*., 2006) as it shown in **Fig. 7**. VanetMobiSim includes macro and micro models in generating a realistic vehicular mobility model. It simulates vehicle behavior such as vehicle decelerates when it approaches the other vehicles or turn at an intersection, the vehicle accelerates when the traffic is sparse and stops when there is a traffic light. In our mobility model, we limit the maximum vehicle speed from 10-40 m $\sec^{-1}$. Although in average, vehicles move below 20 m $\sec^{-1}$ in a city, we want to test the reliability of probabilistic relay under an extremely high speed (30-40 m $\sec^{-1}$). We also set acceleration and deceleration for 0.6 and 0.9 m $\sec^{-2}$. The vehicle length is set to 5 m and safety distance between vehicles is 2 m.

We use IEEE 802.11p as the standard model for Wireless Access in Vehicular Environments (WAVE) (Eichler, 2007) for our MAC model and limit the transmission range of vehicle to 100 m. We adopt the IEEE 802.11p simulation parameters (Chen *et al*., 2007). They set up the parameters for 802.11Ext and WirelessPhyExt in a tcl script of ns-2. Our simulation time is 500 sec, but data packet transmission started at 300 sec. We simulated each protocol at different vehicle speeds. To simplify the simulation, The source is statically placed on the map at (200; 300) while the other vehicles are moving during the simulation. A randomly picked destination is simulated with the static source in our scenarios. We run the simulation five times with different pair for each scenario and then average the results. The other settings of our simulation parameters are shown in **Table 3**. We measure protocol performance in our evaluation based on these following metrics:

- Packet Delivery Ratio (PDR): the ratio between the number of data packets delivered to the receiver and the number of data packets sent by the source
- Routing overhead: the total size of routing packets required to construct and maintain the routes
- Average delay: the average difference between the time when a data packet is originated by the sender and the time when this packet reaches receiver
- Average hop count: the average number of hops needed by the pairs to transmit the data packets
- Number of relay transmissions: the number of relay transmissions as a response for unsuccessful unicast transmissions of packets

We add the beacon message as a routing overhead for AODV-PR and AOMDV-PR. We will show the significant trade-off between PDR and routing overhead of AODV-PR and AOMDV-PR is affected by the adjustment of beacon interval.

3.2. Preliminary Evaluation on Static Network

Before we evaluate those two protocols with mobility scenarios, we show our preliminary experiment of AODV-PR performance for static environment. We randomly placed 50 nodes with their fixed positions. We run the simulation under different intensity range of beacon interval, from 0.5 sec (high intensity) to 10 sec (low intensity). As we can see in **Fig. 8**, the PDR of AODV-PR under 0.5 to 10 sec beacon interval mostly stable at 99%. As the environment is static, the number of possible adjacent nodes which are able to relay unsuccessful transmission are remain unchanged most of the time. The main difference between high and low intensity of beacon interval is obviously in the number of generated beacon messages.

In AODV-PR, beacon message is included as a routing overhead together with RREQ and RREP. **Figure 9** shows the huge gap of routing overhead between AODV-PR and AODV. Under 0.5 sec of beacon interval, AODV-PR generated over 10,000 bytes $\sec^{-1}$ while under 10 sec of beacon interval, it generated almost the same as the original AODV's routing overhead. Thus under very low mobility or static environment, low intensity of beacon interval is preferred to minimize the routing overhead while producing good results in PDR. Because of that huge gap of routing overhead created by the beacon interval below 5, we only set up the beacon interval from 5 to 10 sec for the next evaluation.

3.3. Evaluation Result for Single Connection

As the first evaluation result, **Fig. 10** shows the effect of vehicle mobility on the PDR. AODV-PR(t) and AOMDV-PR(t) are the routing protocols combined with probabilistic relay with beacon interval set to t seconds. Both AODV-PR(5) and AOMDV-PR(5) consistently outperform their original forms under all variation of speed. AODV-PR(5) and AOMDV-PR(5) constantly achieved above 85% under the variation of vehicle speed. It has been confirmed that the addition of probabilistic relay clearly helps routing protocols to improve their PDR. Because of the capability of relaying the unsuccessful data packet transmissions, it can solve connectivity issues in VANETs due to highly dynamic topology. In addition, probabilistic relay does not affect the original behavior of these routing protocols. It only changes how they deal with undelivered unicast packet.

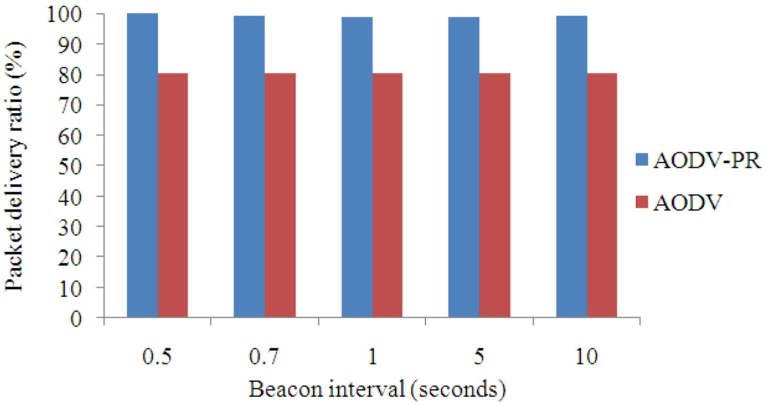


Fig. 8. PDR of various beacon intervals in static environment

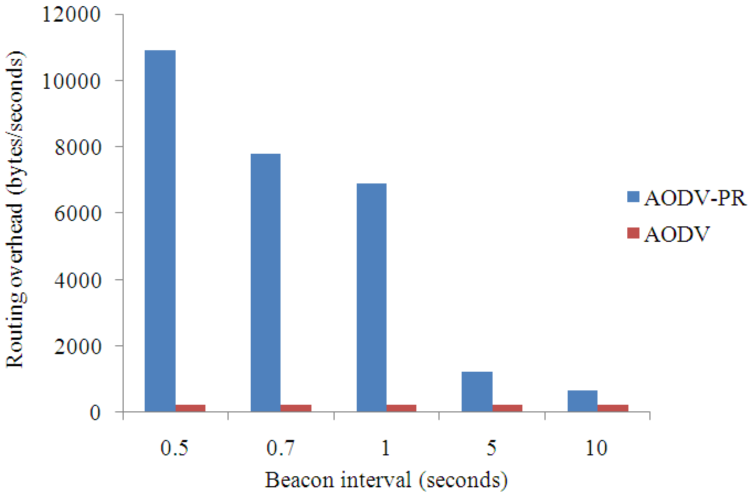


Fig. 9. Routing overhead of various beacon intervals in static environment

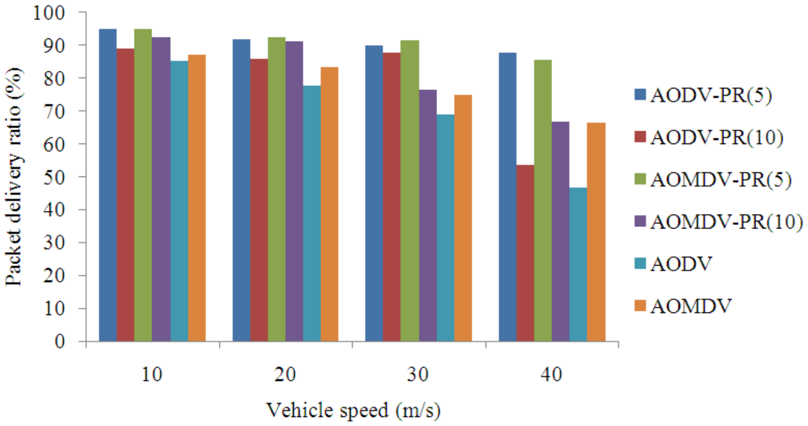


Fig. 10. Packet delivery ratio with single connection

Table 3. Simulation parameters

Networks simulator	ns-2.34
Simulation time	500 sec
Simulation area	500×500 meters^2
Number of vehicles	50 vehicles
Total data packets sent	200 packets
Data type and interval	Constant Bit Rate (CBR)/1 sec
Data packet size	512 bytes
Number of connections	1, 2 UDP Connections
Propagation model	Nakagami
MAC protocol	IEEE 802.11Ext
Routing protocol	AODV and AOMDV
Radio range	100 meters
Maximum vehicle speed	10-40 m sec^{-1} (36-144 km h^{-1})
Beacon interval	5, 10 sec

Meanwhile, AODV-PR(10) and AOMDV-PR(10) produce competitive results with AODV-PR(5) and AOMDV-PR(5) under 10-20 m sec^{-1} in PDR. When the maximum vehicle speed is increasing to 40 m sec^{-1}, AODV-PR(10) and AOMDV-PR(10) cannot hold their PDR. Since they generate beacon message for every 10 sec, they cannot keep updated relaying probability accurately under extremely dynamic environments. At 40 m sec^{-1}, AODV-PR(10) and AOMDV-PR(10) decrease their PDR to 54 and 66%. However, they still achieve slightly better than their original forms. Under low vehicle mobility 10-20 m sec^{-1}, sets up beacon interval for every 10 sec is the appropriate option for AODV-PR and AOMDV-PR since they generate a few number of beacon messages. However, increasing the vehicle speed up to 40 m sec^{-1}, every 5 sec beacon interval is the suitable setup to keep their PDR above 85%. Meanwhile, original AODV and AOMDV are gradually decreased their PDR follow the increasing of vehicle speed. As the speed increases, the topology is frequently changed and their structures are needed to be re-adjusted more often.

In our second evaluation result, **Fig. 11** shows the routing overhead including the beacon message. AODV-PR(5) and AOMDV-PR(5) produce the highest routing overhead compared to the others. Since they generate more beacon messages twice than AODV-PR(10) and AOMDV-PR(10), the routing overhead of AODV-PR(5) and AOMDV-PR(5) achieve over 1300 to 2030 bytes sec^{-1}. On the other hand, AODV-PR(10) and AOMDV-PR(10) produce competitive results with the original AODV and AOMDV especially at 30-40 m sec^{-1}. The number of beacon messages dominates the proportion of routing overhead for both AODV-PR and AOMDV-PR in **Fig. 11**.

However, if we exclude the beacon message and only include RREQ, RREP and RERR as a routing overhead, AODV-PR and AOMDV-PR show competitive results in routing overhead with their original form as it shown in **Fig. 12**. It is obvious that both AOMDV and AOMDV-PR have generated more control packets than AODV and AODV-PR due to their multipath construction and maintenance.

Figure 13 shows the average delivery delay relative to the vehicle mobility. Both AODV-PR(5) and AOMDV-PR(5) produce competitive results for several cases. Since they have adjacent vehicles to relay unsuccessful transmission, AODV-PR(5) and AOMDV-PR(5) reduce the waiting time for retransmission. Moreover in certain situation, they need to execute route discovery process to maintain their topology. Thus, it increases packet delivery delay. Meanwhile, AODV-PR(5) and AOMDV-PR(5) occupied adjacent vehicles to relay unsuccessful transmission rather than waiting for retransmission. Thus, this mechanism greatly reduced packet delivery delay. However, under 20-40 m sec^{-1} AODV-PR(10) significantly added more delivery delay than the others.

Since the exchange of the beacon message is transmitted every 10 sec, it is not enough to recover from the highly dynamic environments. AOMDV takes the advantages of its multipath to reduce route discovery process. Even if the main route is broken, it has several alternative paths to use. Meanwhile, AODV only maintains unipath for each destination. It needs to perform route discovery process if that unique route is broken. Thus, it increases the packet delivery delay.

In our forth metrics, we show the average number of hops in **Fig. 14**. The addition of probabilistic relay clearly does not add a huge number of extra hops in our simulations. They have competitive results compared to their original forms. The average number of hops for AODV-PR(5) ranged from 2.5 to 3.5 hops and that for AODV-PR(10) ranged from 2.6 to 2.9 hops while original AODV ranged its average number of hops from 2.3 to 3.4 hops. On the other hand, AOMDV and AOMDV-PR produce lower hop counts than AODV and AODV-PR in our simulation.

For our next metric, we want to show our evaluation result in the number of relay transmissions by adjacent nodes, when we add probabilistic relay into routing protocols. **Figure 15** shows that the trend of the number of relay transmissions for both AODV-PR and AOMDV-PR is gradually increased at 10-30 m sec^{-1}. At 10 m sec^{-1} where the topology is less dynamic than at 20-30 m sec^{-1}, AODV-PR achieves from 2.8 to 3.4 number of relay transmissions/seconds. On the other hand, AOMDV-PR varies from 2.1 to 4.3 number of relay transmissions/seconds. At 20-30 m sec^{-1} where the topology is started to become highly dynamic, both AODV-PR and AOMDV-PR increase the number of relay transmissions. However at the range of 30-40 m sec^{-1}, their number of relay transmissions is decreased.

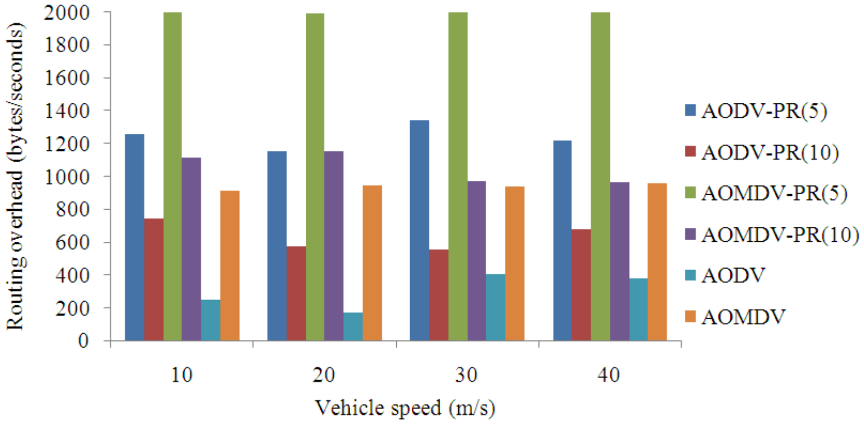


Fig. 11. Routing overhead with single connection

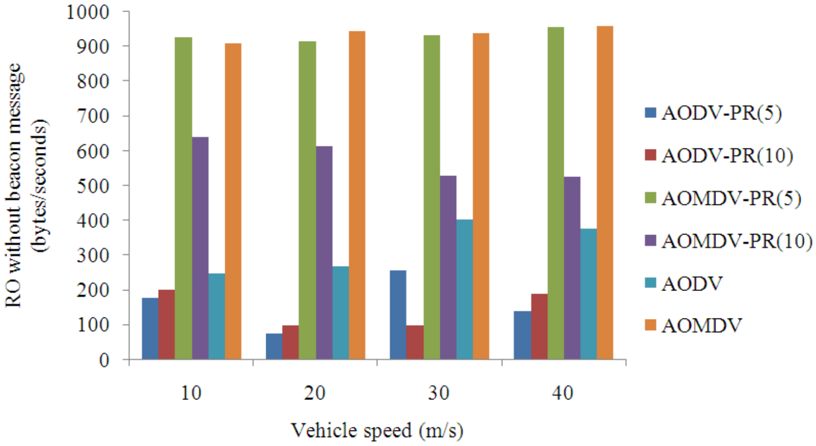


Fig. 12. Control overhead with single connection

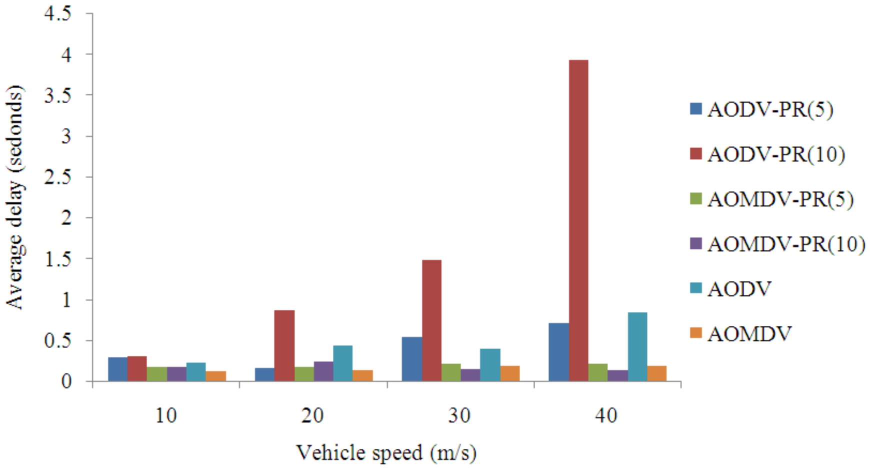


Fig. 13. Average delay with single connection

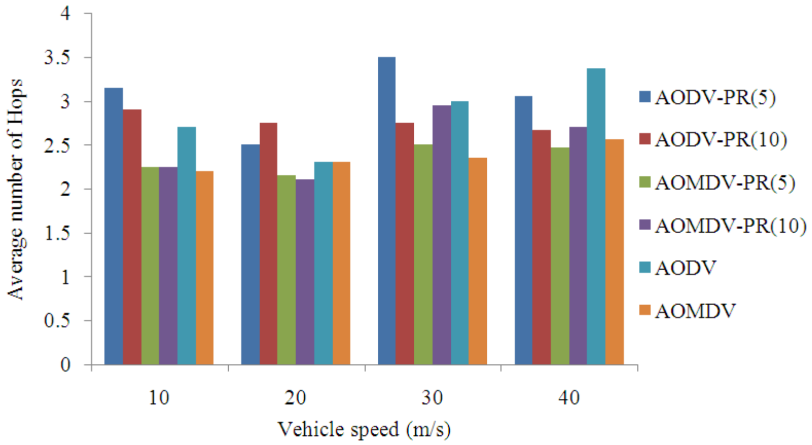


Fig. 14. Average number of hops with single connection

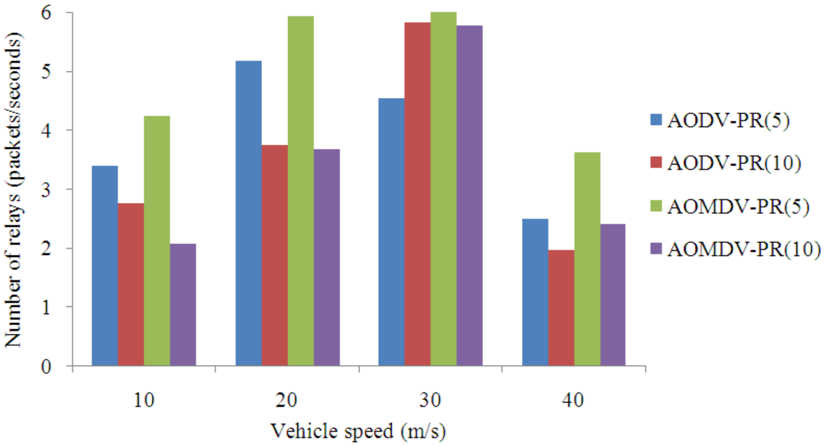


Fig. 15. Number of relay transmissions with single connection

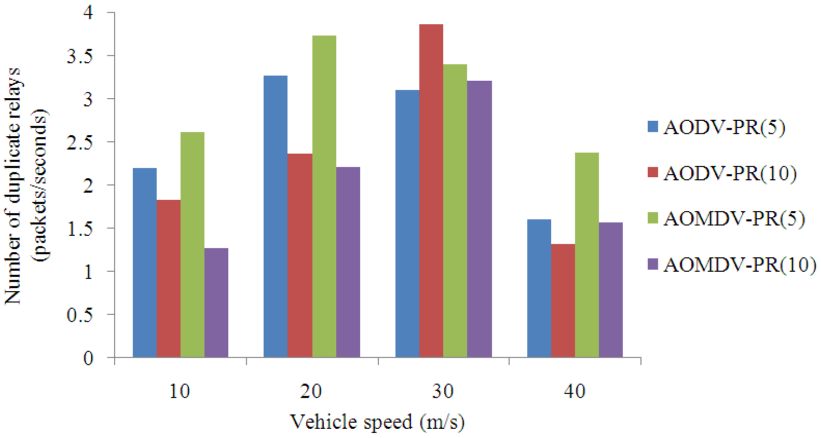


Fig. 16. Number of duplicate relays with single connection

An extra evaluation that we want to show is the number of duplicated relay transmissions which are as known as false positives, relaying packets that are already at the destination. **Figure 16** shows the number of duplicated relay transmissions as a function of vehicle speed. Under 10-30 m $\sec^{-1}$, both AODV-PR and AOMDV-PR produce up to 2-3 numbers of duplicate relay transmissions/seconds. However, at 40 m $\sec^{-1}$, AODV-PR and AOMDV-PR decrease the number of duplicate relay transmissions. The trend of the number of duplicate relay transmissions is proportional with the result in **Fig. 15**.

3.4. Evaluation Result for Multiple Connections

On the next scenario, we evaluate the performance of routing protocols with and without probabilistic relay for multiple connections. We select two random pairs and create two UDP connections. We run the simulation for several different pairs and average the results. **Figure 17** shows the PDR of multiple connections against the variation of vehicle speed.

The addition of probabilistic relay into AODV-PR and AOMDV-PR for multiple connections still produces better performance than the original forms of AODV and AOMDV. In Multiple connections, AODV-PR(5) and AOMDV-PR(5) still outperform AODV-PR(10) and AOMDV-PR(10), since they set up a 5 sec beacon interval. Nevertheless, comparing to the single connection, the gap between those two different beacon intervals is not as huge as in the single connection, especially under 40 m $\sec^{-1}$. For a single connection, the gap of PDR between AODV-PR(5) and AODV-PR(10) at 40 m $\sec^{-1}$ is 34% while the gap between AOMDV-PR(5) and AOMDV-PR(10) at 40 m $\sec^{-1}$ is 21%.The gap of PDR between AODV-PR(5) and AODV-PR(10) for multiple connections is only 8% while their gap at 40 m $\sec^{-1}$ is 6%.

In our second evaluation result for multiple connections, we measure the performance of both protocols for their routing overhead as it shown in **Fig. 18**. Original AOMDV clearly has generated more control packets than AODV. Its multipath for multiple connections needs to be maintained exclusively than unipath of AODV. Original AODV averages for 747.39 bytes $\sec^{-1}$ and 1021.8 bytes $\sec^{-1}$ for AOMDV. Meanwhile probabilistic relay protocols, AODV-PR(5) and AOMDV-PR(5), generate almost double routing overhead than their original forms. Their averages are 1506.3 bytes $\sec^{-1}$ for AODV-PR(5) and 2075.1 bytes $\sec^{-1}$ for AOMDV-PR(5). However for 10 $\sec^{-1}$ beacon interval, AODV-PR(10) and AOMDV-PR(10) maintain competitive routing overhead with the original AODV and AOMDV. Compared to their original forms, AODV-PR(10) only gained for about 11.2 bytes $\sec^{-1}$. Meanwhile, AOMDV-PR(10) produces a lower routing overhead than AOMDV. Thus for multiple connections, setting up the beacon interval for every 10 sec is the suitable option to avoid a large number of routing overheads while holding up the PDR above their original forms.

In terms of average delivery delay for multiple connections as it shown in **Fig. 19**, both AODV-PR(5) and AOMDV-PR(5) produce very competitive results with their original forms especially under 10-30 m $\sec^{-1}$. However, at 40 m $\sec^{-1}$ AODV-PR(5) and AODV-PR(10) drastically increased their average delay up to 1.1 and 1.3 sec, respectively. Meanwhile, at 40 m $\sec^{-1}$, AOMDV-PR is still able to keep a competitive result with its original form. At any variation of speed, AODV-PR(10) produces the highest average delay among the others. Its 10 sec beacon interval is not able to hold their neighborhood information updated any longer. Thus, AODV-PR(10) gradually increased its average delay. Original AOMDV achieves the average delay below 0.2 sec. Its multipath construction surely helps to avoid route discovery process if the main route is broken. Thus, it can save more time than AODV's unipath.

As the next evaluation result, **Fig. 20** stated that probabilistic relay does not add huge number of extra hops for multiple connections. AODV-PR and AOMDV-PR produce almost the same results as their original forms. In average, AODV produces 3.2 hops while AODV-PR(5) and AODV-PR(10) achieve 3.3 and 3.4 hops, respectively. AOMDV produces lower hops than AODV. It achieves 2.5 hops in average. Meanwhile AOMDV-PR(5) and AOMDV-PR(10) produce 2.6 and 2.4 hops, respectively. There is no big gap of average number of hops between single and multiple connections in our simulation.

For the last performance metric, we measure the number of relay transmissions in multiple connections scenarios as it shown in **Fig. 21**. As it compared to a single connection, the trend of the number of relay transmissions for both AODV-PR and AOMDV-PR is also gradually increased at 10-30 m $\sec^{-1}$ and decreased at 40 m $\sec^{-1}$. In average, AODV-PR(5) and AODV-PR(10) achieve 4.7 and 2.9 number of relay transmissions/seconds while AOMDV-PR(5) and AOMDV-PR(10) achieve 4.5 and 0.6 number of relay transmissions/seconds. **Figure 22** shows the number of duplicated relay transmissions in multiple connections. It also has a similar trend as in a single connection. Under 10-30 m $\sec^{-1}$, both AODV-PR and AOMDV-PR produce up to 3.1-2.8 numbers of duplicate relay transmissions/seconds in average. However, at 40 m $\sec^{-1}$, AODV-PR and AOMDV-PR decrease the number of duplicate relay transmissions.

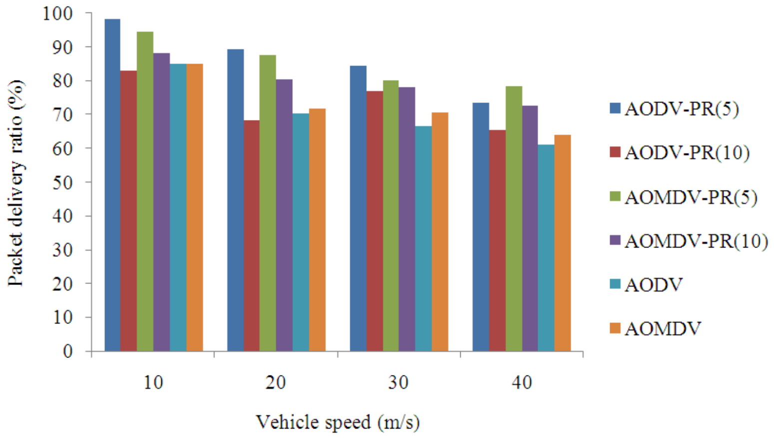


Fig. 17. Packet delivery ratio with multiple connections

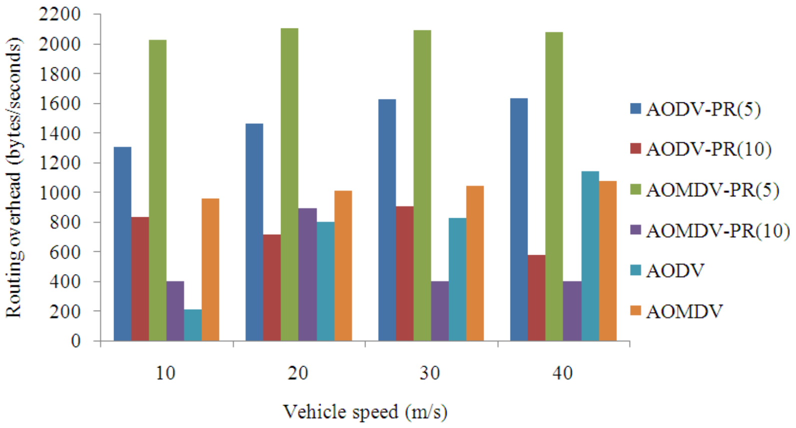


Fig. 18. Routing overhead with multiple connections

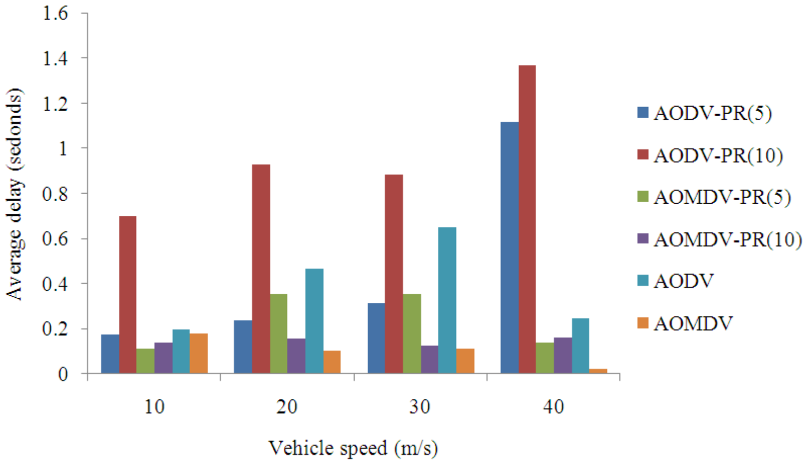


Fig. 19. Average delay with multiple connections

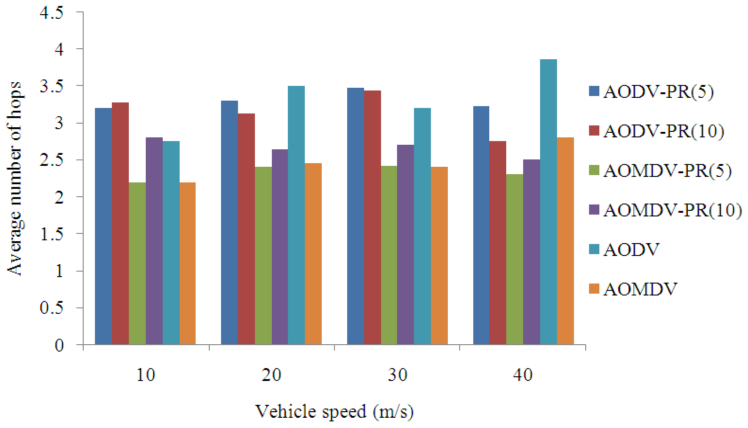


Fig. 20. Average number of hops with multiple connections

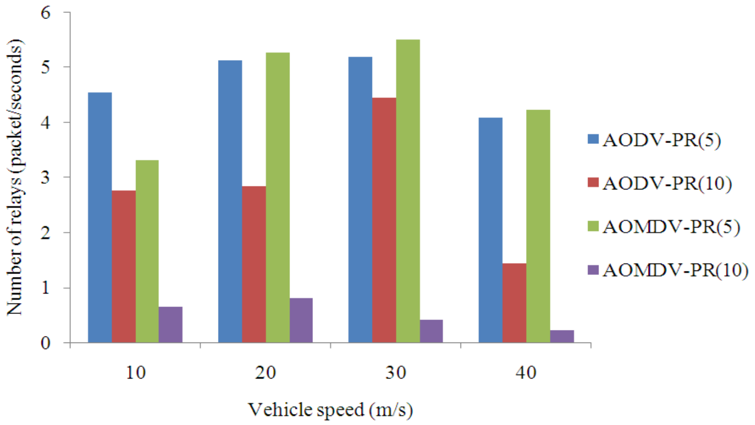


Fig. 21. Number of relay transmissions with multiple connections

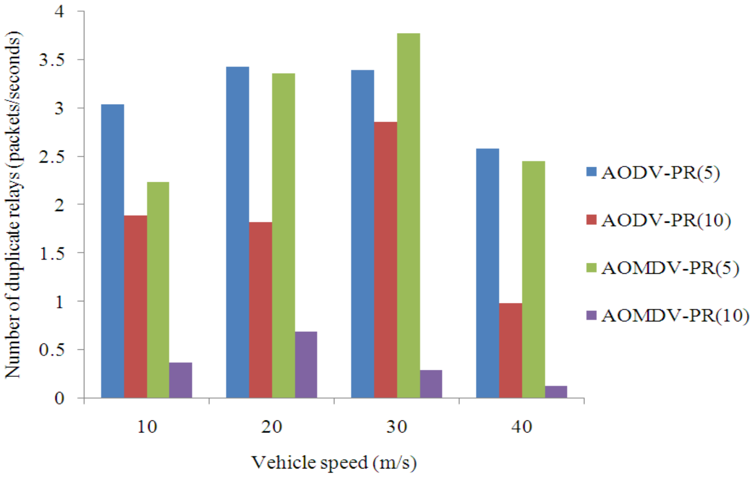


Fig. 22. Number of duplicate relays with multiple connections

4. CONCLUSION

In this study, we showed that the addition of probabilistic relay into AODV and AOMDV clearly improved their performance. Both AODV-PR and AOMDV-PR outperform their original forms in Packet Delivery Ratio (PDR). Probabilistic relay allows vehicle to exploit the advantages of sender diversity by leveraging adjacent vehicles to deal with retransmission of undelivered unicast packet. Probabilistic relay only makes a change in the link layer level of the protocols. AODV-PR(5) and AOMDV-PR(5) are the original AODV and AOMDV with probabilistic relay and have been set their beacon interval for every 5 sec while we set 10 sec beacon interval for AODV-PR(10) and AOMDV-PR(10).

Under different variation of vehicle's speed, AODV-PR and AOMDV-PR produce better PDR than AODV and AOMDV, respectively, for single and multiple connections. In scenario of single connection, AODV-PR(5) and AOMDV-PR(5) produce consistent results especially under 40 m $\sec^{-1}$. Since they generate more intensive beacon messages for every 5 sec, they can keep their updated relaying probability accurately. Meanwhile, AODV-PR(10) and AOMDV-PR(10) drop their PDRs significantly under 40 m $\sec^{-1}$. However, since they generate lower beacon messages than 5 sec beacon interval, they clearly produced lower routing overhead than AODV-PR(5) and AOMDV-PR(5). For scenario of multiple connections, AODV-PR and AOMDV-PR still outperform their original forms in PDR. There is no significant gap between 5 and 10 sec beacon intervals even at 40 m $\sec^{-1}$. The addition of probabilistic relay also does not give a bad impact on average delay and hop counts.

In short, the addition of probabilistic relay into AODV-PR and AOMDV-PR clearly improved PDR. For a single connection and extremely dynamic environment, 5 sec beacon interval is preferred to hold their performance in PDR. However, it creates a huge gap of routing overhead compared to their original forms. On the other hand, setting up the beacon interval into 10 sec produced a competitive routing overhead with the original form of protocols. 10 sec beacon interval is also suitable for multiple connections since it does not create a large gap of PDR with 5 sec beacon interval's protocols. Since probabilistic relay only affects the MAC layer, it can be added into any unicast protocols including VANETs protocols such as CAR. For our future work, we will evaluate VANETs protocols with probabilistic relay performance under different VANET scenarios in terms of varying the mobility model and generated map. We will also try to reduce a huge number of unnecessary redundant relay transmissions. Thus, calculation of relaying probability needs to be improved.

5. ACKNOWLEDGEMENT

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