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Nexthop selection mechanism for nodes with heterogeneous transmission range in VANETs

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ABSTRACT

The frequent relocating of vehicles will significantly degrade the routing performance of a VANET. One of the proposed routing approaches to relieve this drawback adopts a greedy fashion to relay the packets hop-by-hop by selecting the nearest neighboring vehicle to the destination as the nexthop forwarder. It is an efficient method of packet routing when the transmission range of each vehicle in the VANET is of the same fixed length. Recently, as heterogeneous wireless networks have become popular, wireless terminals are generally equipped with multiple wireless access network interfaces to improve the quality of transmission and to gain a good signal while relocating. However, the greedy approach of nexthop forwarder selection will not always use the minimum hop counts of the routing path for VANET heterogeneous transmission range nodes. In this paper, we propose a nexthop selection mechanism for VANETs which takes the heterogeneous environment into consideration. A minimum hop count prediction method is firstly proposed to help the current packet-carrying vehicle node to estimate the minimum hop counts required from each neighbor to the destination. Subsequently, based on the estimated values, the routing decision can be made. The simulation results show that our proposed method exhibits better performance in terms of the average end-to-end delay and the packet delivery ratio comparisons than the compared methods.

1. Introduction

In recent years, the popularization of network applications has given impetus to the increasing number of Internet users, and has also stimulated the advancement of network technologies. As a rapidly increasing amount of useful information can be retrieved from the Internet to assist us with the needs of our daily life, the time period spent online each day has been greatly extended. Nowadays, people use handy devices (for example, tablet personal computers and smart-phones) as platforms to access the Internet more frequently than via desktop personal computers. Consequently, the features of network equipment have evolved from heavy to light, stationary to mobile, and wired to wireless access. Wireless technologies are thus becoming increasingly important, since wireless access can gain good flexibility and ease of Internet access.

VANETs are one of the promising wireless technologies that are largely applied to enhance driving safety and passenger comfort. For example, through the dissemination of warning messages regarding a car accident via a VANET, some vehicles might avoid a collision since the braking triggered by receiving a warning message is much earlier than that triggered by a visual reaction. A VANET can also guide drivers to avoid traffic congestion to increase driving safety and shorten travel time. In addition to smart road guidance, a VANET can also provide location services for passengers, perceive nearby restaurants and gas stations, or even provide the local weather information.

In recent years, VANETs have evolved rapidly due to their diverse and useful applications, but several technical problems still remain to be resolved [1–3]. For instance, the high velocity of moving vehicles causes frequent changes in network topology, and consequently the inter-vehicle communication links will be unstable or may even become disconnected. For routing between the source and the destination in a VANET, a sequence of road segments is generally preplanned by routing protocols. For the routing within each road segment, a greedy forwarding approach is the most frequently used method of packet relaying. In this approach, the current packet-carrying node will choose one of the vehicles among its neighboring set that is located in the forwarding direction and then forward the packets to the chosen nexthop forwarding node.

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Note that it will not be possible for the vehicles in the neighboring set located in the opposite direction of the forwarding to be chosen as a nexthop forwarding node. Thus, we will exclude these vehicles from our considerations. For ease of discussion, the neighboring set that is used throughout this paper excludes the vehicles in the opposite direction of the forwarding.

The selection criterion is generally to adopt the nearest node to the next junction in the neighboring set. The same greedy relaying operations are repeated until the next junction is reached. Generally, the number of hops for a packet to travel from the source to the destination via such a greedy approach is the minimum under the assumption of each vehicle being equipped with a homogeneous transmission range antenna. However, it will not always be true for heterogeneous transmission range antenna nodes in a VANET.

As diverse coverage ranges of wireless technologies evolve (such as the technologies of WLAN, WMAN, and WWAN), these wireless networks are generally deployed in our environment and overlap each other. For high quality transmission service and good signal capture, some mobile terminals have multiple wireless access network interfaces installed. Such wireless terminals are called multi-mode mobile terminals, and the hybrid network is called a heterogenous wireless network [4–15]. With the services of the heterogeneous wireless network, the users can gain benefits of flexible wireless transmission. In the VANET environment, although the IEEE 802.11p has become the standard of the access network interface, its short coverage and the fast-moving vehicles generally result in a large packet loss and long delays. In order to facilitate the different transmitting purposes of vehicle passengers, vehicles might also be equipped with different capabilities of wireless network interfaces to provide parallel network channels for packet transmission to enhance the network performance [8–15]. A survey article [10] also concludes that an Advanced Heterogeneous Vehicular Network (AHVN) which uses multiple access technologies (such as IEEE 802.11p, IEEE 802.16, IEEE 802.15.3, and Cellular networks) in a collaborative manner could be the best candidate to support most of the applications of VANETs.

In a realistic environment, different types of vehicles might coexist on the road. The memory (storage) capacity, the processing power, or even the transmission range of different types of vehicles may not be homogeneous. Rather, for certain specific application objectives, some vehicles may be equipped with multiple interfaces with different length transmision range antennas than others to enlarge their service range (such as buses). Some studies [12–15] also consider that a VANET environment consists of two kinds of vehicles to communicate on the road: ordinary vehicles with short-range radio interface, and public transit vehicles (such as buses) equipped with long-range and short-range radio interfaces.

In this research, we consider a packet relaying problem with heterogeneous transmission range nodes in a VANET. Assume that a VANET is composed of vehicles belonging to k different classes, each with transmission range r_i, $1 \leqslant i \leqslant k$. Note that this is a generalization of the traditional VANET environment, whereas the value k is equal to 1 for the traditional case. Throughout this paper, we will use $k = 2$ as the numerical example, that is, the vehicles are classified as buses and ordinary cars. Note that there are several luxury cars equipped with more advanced radio communication facilities. However, due to buses having fixed trajectories and generally being able to play the role of message ferries [16–21] to assist VANET communication, we therefore take them to be the example of a vehicle type equipped with longer transmission range antennas and larger buffer size.

According to the above-mentioned selection rule of a greedy routing approach in a homogeneous environment (we call it the traditional greedy routing approach), the current packet-carrying vehicle node will choose the nearest vehicle to the next forwarding junction in the neighboring set to be the nexthop forwarder. However, this greedy approach will not always gain the minimum hop counts in the heterogeneous case.

In the following, a counter example to illustrate the violating instance is given. In a vehicle fleet, a member vehicle (the source node S shown in Fig. 1(a)) has to constantly report its position to the leader vehicle (the destination node D shown in Fig. 1(a)). According to the rule of the traditional greedy routing method, the source node will firstly choose the vehicle that is located in its transmission range and is the nearest vehicle to the destination node (see the car that is marked with the first arrow in Fig. 1(a)). The packets will then be forwarded from the source to the chosen nexthop forwarder. Again, the chosen car will select the nearest vehicle to D in its neighboring set to be the nexthop forwarder. Fig. 1(a) shows that there are 6 hops in total on the routing path from the source to the destination. However, on the contrary, if the source node chooses the nearest bus to destination D, then the total hop count may drop to 5 hops in total (see Fig.1(b)). This is because the traditional greedy routing method only forwards packets to the nearest neighboring vehicle to the destination. In the case of the chosen vehicle being a bus, then it might shorten the number of hops for later communications. Of course, if a vehicle solely selects the nearest bus located in the transmission range to the destination as the nexthop forwarder, it will again be a naive and improper approach since one has to take the locations and the densities of both types of vehicle into consideration to gain the

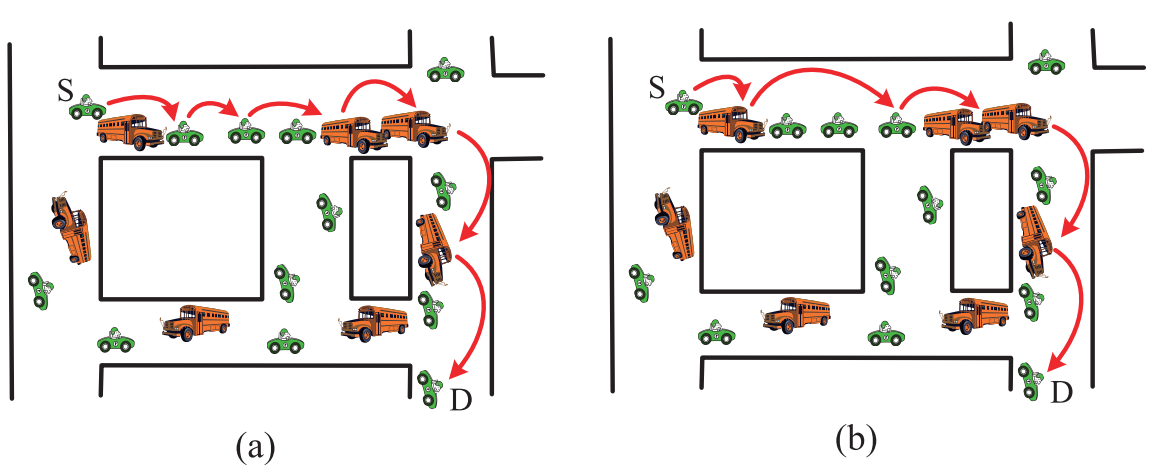

Fig. 1. A counter example to illustrate that the traditional greedy routing approach in a heterogeneous case will not always gain the minimum hop routing.

least number of hop counts. This example is only one instance of the traditional greedy routing approach not always being the best policy in the heterogeneous case. In this paper, we have designed a nexthop selection mechanism to minimize the total hop counts of the end-to-end routing path under k types of heterogeneous transmission range vehicle nodes in a VANET. A prediction method called the Stochastic Minimum-hops Forwarding Prediction Method (SMFPM) is firstly developed to estimate the minimum hop counts from a vehicle node to the next forwarding junction. Subsequently, using the SMFPM method, a nexthop selection routing method called the Stochastic Minimum-hops Forwarding Routing (SMFR) is proposed to help the current packet-carrying vehicle node to properly select the nexthop forwarder to try to meet the design objective. The SMFPM and the SMFR methods are described in detail in Section 3. Our method has the following features:

1. We generalize the heterogeneous vehicle types from two types (buses and ordinary cars) to k types of vehicles.
2. An expected value of the hop count estimation method is proposed to determine the minimum hop counts from each vehicle of type i ($1 \leqslant i \leqslant k$) to the next forwarding junction. Our proposed routing algorithm adopts the estimation method for the forwarding decision to reduce the hop counts required in routing.

The remainder of this paper is organized as follows. In Section 1, the motivation and the routing scheme for the heterogeneous transmission range nodes case are discussed. In Section 2, the related works are described. In Section 3, our considered environment features and the proposed method, Stochastic Minimum-hops Forwarding Routing (SMFR), are then discussed. The simulation results and the concluding remarks are discussed in Sections 4 and 5, respectively.

2. Related works

Due to the character of frequently broken communication links in VANETs, traditional table driven routing protocols based on the Bellman-Ford algorithm (for example, the Destination-Sequenced Distance Vector (DSDV) [22] or Dynamic Source Routing (DSR) [23], etc.) are no longer fit for such an environment. These routing protocols all behave poorly in a VANET environment, since the quick roaming speed of vehicles will frequently break the communication paths. Generally, the vehicle nodes have to use a store-carry-forward fashion to relay the transmitted packets. That is, in case of a current packet-carrying vehicle node having no neighbor located in its transmission range, then the carrier will continue carrying the packets until a neighbor shows up. Once the neighbor set becomes non-empty, the carrying vehicle will choose a neighbor as the nexthop forwarder and then relay the carrying packets to the chosen one.

To date, several routing protocols have been proposed for VANET environments. These protocols can be classified into the following categories of approaches. The first category of routing protocols uses on-demand and multiple paths for automatically switching routing paths from a broken one to another (such as On-demand Multipath Distance Vector (AOMDV)) routing protocol [24–26], which is extended and modified from the Ad hoc On-demand Distance Vector (AODV) routing protocol [27]. The second category of routing protocols is the position-based routings (or the Geographic routings) [28,29]. Generally, most of the vehicles on the road are equipped with a GPS facility and digital maps for navigation. These vehicles can thus be easily aware of their geographical locations and then use this information to enhance the routing performance.

In [28], a routing protocol called the GPSR (Greedy Perimeter Stateless Routing) is proposed to use the location information of nearby neighboring vehicles and then chooses the nearest neighboring node to the destination to be the nexthop relaying node. The literature [29] indicates that the greedy approach of the GPSR has some flaws in the junction area since a routing loop might occur. A routing protocol called the GPCR (Greedy Perimeter Coordinator Routing) is also proposed to use a right-hand rule in the junction area to overcome the drawback of the GPSR. The right-hand rule suggests that the current packet-carrying vehicle node select the vehicle that is nearest to the destination on its right-hand side to be the nexthop forwarder. The nexthop forwarder will repeat the same operations until the junction area has been passed. The operations are the same as the GPSR when not in the junction area.

The above-mentioned routing protocols focus mostly on dense vehicle environments. However, in a sparse area (such as in the countryside), the network topology might be disconnected most of the time. In this case, poor routing performance might be experienced when applying previous routing protocols in such a sparse environment. The other research subject called DTN (Delay-tolerant network) routing aims to design suitable routing mechanisms for such environments. Several routing protocols have also been proposed for the DTN routing problem [16–21,30–34]. Among these studies, Vahdat and Becker [31] used an Epidemic approach while Costa et al. [32] and Daly and Haahr [33] used the Social network approach to design protocols for such environments. Message ferrying is another efficient approach [16–21] to reconnect the disconnected components of a network via regularly dispatching ferries within the network environment. These regular roaming ferries (with fixed route and fixed dispatching frequency) can help to better perform the message relaying task than other randomly roaming vehicles in a sparse environment.

Let us turn our attention back to the dense vehicles case (such as urban environments). In such an environment, most of the proposed routing protocols (such as the GPSR [28] or the GPCR [29]) aim at how to relay the packets efficiently and quickly to the destination along the sequence of road segments. As previously mentioned, these protocols use a greedy approach to select the nearest vehicle among the neighboring set of the current packet-carrying node to be the nexthop forwarder. However, in an urban environment, there are at least two kinds of vehicle (for example, buses and ordinary cars) [12–15]. Under this assumption, as mentioned in Section 1.1, the nexthop forwarder selection mechanism will significantly affect the routing performance (such as the length of the routing path). In [12–15], the authors considered the routing problem for the heterogeneous vehicles case (the number of vehicle types is equal to 2; that is, $k = 2$) in an urban environment. The literature [14] noted that the vehicles in the road segments move like clusters due to the effect of the traffic lights. The author uses the buses in each cluster to play the role of cluster heads, and these clusters form a mobile backbone. It is also assumed that the buses are equipped with two wireless transmission interfaces (one of them has a longer transmission range r_{bus}, and the other has a shorter transmission range r_{car}; $r_{bus} > r_{car}$), while the ordinary cars are only equipped with a single type of wireless transmission interface (the shorter transmission range r_{car}).

A routing protocol called the MIBR in [14] is proposed for considering the heterogeneous case of an environment where $k = 2$. The MIBR routing protocol consists of two components, which include the route selection mechanism and the forwarding mechanism. The route selection mechanism firstly determines the link cost with respect to each road segment. Each link cost is synthesized by the density of the buses and the length of the respective

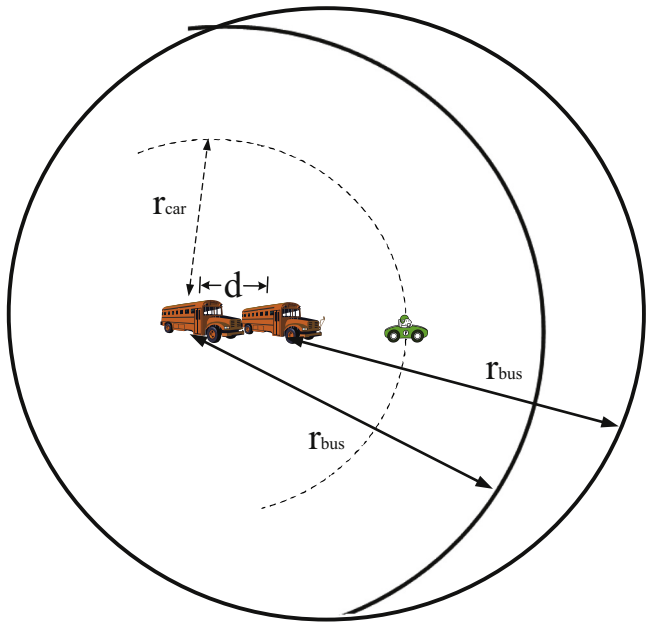

Fig. 2. An illustration to demonstrate the forwarding decision making of the MIBR [14].

road segment. Then, by applying Dijkstra's algorithm using the network topology and the cost function, an optimal route will be determined. For the forwarding mechanism in each road segment of the determined route, the authors use a "bus first" strategy to select the bus that is the nearest to the destination within the transmission range of the current packet-carrying vehicle node to be the nexthop forwarder. They also point out that in the case of the chosen bus being too close to the current carrier, an ordinary car will tend to be selected as the next forwarder rather than the bus (as shown in Fig. 2). The literature [15] also proposes a similar routing protocol called the MIRT which takes the heterogeneous case into consideration. However, neither of these protocols provides a precise forwarding method to clearly determine whether the nexthop forwarder is a bus or an ordinary car depending on the length (d) shown in Fig. 2.

3. The proposed method

Assume there are k types of vehicle in our considered environment. Let the transmission ranges (and the population density) of type i vehicle be r_i (and ρ_i), $1 \leqslant i \leqslant k$, respectively. Without loss of generality, we let $r_1 \leqslant r_2 \leqslant \ldots \leqslant r_k$. We also assume that each vehicle is equipped with some sort of GPS facility for enabling the vehicle node to be aware of its location. In addition, each vehicle node can be aware of its one-hop neighbors within its transmission range through the exchange of beacon messages. The population density (ρ_i) of type i, $1 \leqslant i \leqslant k$ on a road segment can be estimated as follows. A vehicle or a roadside unit located at a junction point will firstly trigger the computing process by broadcasting a request message to gather the related information of each vehicle (such as its position and the number of vehicle types) located in the forwarding direction lanes of the road segment. When a vehicle receives a request message, it will send back a response message to provide the required information. After collecting all of the information, one can easily determine the population density of each vehicle type and then broadcast the results to notify any vehicle located in the road segment and the new incoming vehicles as well. Note that the above process can be performed for each given time period to refresh the population densities.

The main idea of our proposed method is that we use the population density (ρ_i) and the transmission range (r_i) of each vehicle type i, $1 \leqslant i \leqslant k$ in a road segment to predict the minimum number of hops required from any given vehicle node to the next forwarding junction. We call the prediction method *Stochastic Minimum-hops Forwarding Prediction Method* (SMFPM). Using the prediction method SMFPM, we calculate the number of predicted hops from each nexthop forwarder candidate within the neighboring set of the carrier vehicle to the junction point. The forwarding decision can then be made by choosing the neighbor with the minimum number of prediction hops to be the nexthop forwarder and to relay the packets from the current carrier to the chosen one. We call the above routing method the *Stochastic Minimum-hops Prediction Routing* (SMPR). Due to the driving speed and the direction of

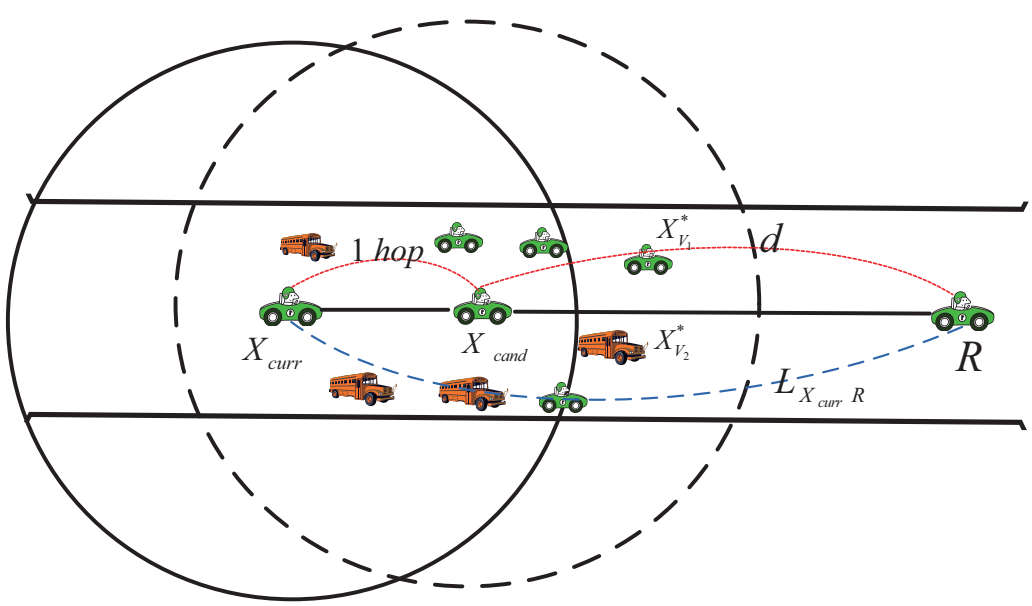

Fig. 3. An illustration of the considered environment.

each vehicle frequently changing, the network topology is consequently altered dramatically. Thus it might happen that the current shortest route between two VANET vehicles at the present time will not be the shortest one after performing a few hops of packet forwarding. In order to overcome the above drawback, our proposed prediction method adopts a stochastic approach by using the population density of each type of vehicle to estimate the expectation value of a shortest path length to overcome the deviation. Based on these values, the routing decision can then be made to enhance the network performance. In the following, we describe the prediction method SMFPM in detail in Section 3.1. Then the complete routing algorithm of SMPR is given in Section 3.2.

3.1. The stochastic minimum-hops forwarding prediction method (SMFPM)

A routing path between a source node and a destination node in a VANET can be represented by a sequence of road segments. The routing within each segment can be accomplished from a current carrier hop-by-hop to the next junction point. Let X_{curr} be the vehicle that is the current packet carrier, and let the position of the next junction point be R. Since any vehicle located within the neighboring set (N) with respect to X_{curr} is a candidate for the nexthop forwarder, we denote it by $X_{cand} \in N$. The length between X_{curr} and the position R is denoted by $L_{X_{curr}R}$. And the length between X_{curr} and the position X_{cand} is denoted by $L_{X_{curr}X_{cand}}$. Note that the value of $L_{X_{curr}X_{cand}}$ can be easily obtained by estimating the delay of exchanging beacon messages, and requires only one hop of communication. For the estimation of the distance $L_{X_{curr}R}$, the vehicle X_{curr} can firstly obtain its own location via the GPS device and can also obtain the position of the next junction point R from the digital map. Then the distance $L_{X_{curr}R}$ can be determined by calculating the distance between these two positions. The distance between X_{cand} and R can be easily determined by $L_{X_{curr}R} - L_{X_{curr}X_{cand}}$. For ease of representation, we use d to denote this value (the relationship between these vehicles is shown in Fig. 3).

Note that the communication between X_{curr} and X_{cand} is only one hop. However, the number of hops from X_{cand} to the junction point R is unknown. In the following, we develop a stochastic estimation method to estimate the minimum number of hops between X_{cand} and R. For the estimation, the vehicle X_{cand} will be regarded as the new current nexthop forwarder that is holding messages and is ready to relay. On the other hand, the neighbors of X_{cand} (e.g., the vehicles $X^*_{V_1}$ and $X^*_{V_2}$ in Fig. 3) will become the new candidates for the nexthop forwarder.

Let the population density and the transmission range of vehicle type i within the current road segment be ρ_i and r_i $(1 \leqslant i \leqslant k)$, respectively, and let the vehicle type of X_{cand} be p. Then, the approximate number n_i of vehicle type i $(1 \leqslant i \leqslant k)$ in the neighboring set of X_{cand} can be easily determined by the following equation.

$$n_i = \rho_i \cdot r_p, \quad \forall i \in \{1, 2, \ldots, k\} \tag{1}$$

Note that, although each vehicle of type i $(1 \leqslant i \leqslant k)$ within the transmission range of a forwarding decision vehicle X (or the X_{cand} in Fig. 3) can be one of the candidates for the nexthop forwarder, the nearest vehicle of type i in N to the next junction point R will obviously dominate the other vehicles of type i as it will have a fewer number of hops to R than the others. We denote the nearest vehicle of type i $(1 \leqslant i \leqslant k)$ in N to the next junction point R by $X^*_{V_i}$. Thus the nexthop forwarder candidate set C can shrink from the neighboring set N to the collection of each nearest vehicle of type i $(1 \leqslant i \leqslant k)$ to R (that is, $C = \{X^*_{V_i} \mid$ for all vehicles of type $i\}$). Let X denote the current nexthop forwarder decision vehicle with type

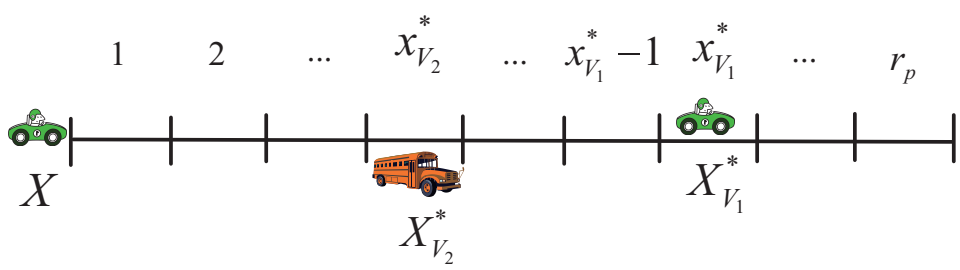

Fig. 4. The illustration for the locations of the nearest vehicles $X^*_{V_1}$ and $X^*_{V_2}$ of type 1 and 2, respectively, to the next junction point R.

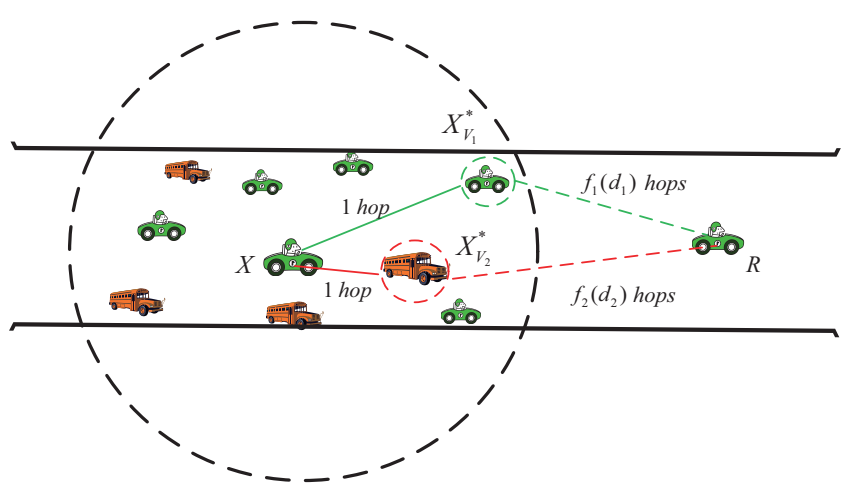

Fig. 5. An illustration of the locations of the nearest vehicle $X^*_{V_1}$ and $X^*_{V_2}$ of type 1 and 2, respectively, to point R.

p $(1 \leqslant p \leqslant k)$ where r_p denotes its transmission range. In the following we will firstly deduct the probability of vehicle $X^*_{V_i}$ showing up at position (l), where $1 \leqslant l \leqslant r_p$. As shown in Fig. 4, we partition the transmission range of X into r_p unit length and let the vehicle $X^*_{V_i}$ of type i be located in position $x^*_{V_i}$ $(1 \leqslant i \leqslant k)$.

Assume that the n_i type i vehicles are uniformly distributed along the entire forwarding direction of transmission area X. Thus the probability of each vehicle being located in each unit length of area is equal to $1/r_p$. Since the nearest vehicle $X^*_{V_i}$ to R is located at l (that is, $x^*_{V_i} = l$), then the following two conditions must hold: (1) there will be no type i vehicle shown in positions $l+1$ to r_p, and (2) at least one vehicle of type i will be located at position l. Note that the probability of all possible location outcomes for n_i vehicles that fall within positions ranging from 1 to l will be equal to $[l/r_p]^{n_i}$. The probability of the event of vehicle $X^*_{V_i}$ being located in position l is thus equal to all of the above mentioned possible outcomes to remove the outcomes that all type i vehicles fall within the range of 1 to $l-1$ (that is, no vehicle is located at position l). Thus, we have,

$$P^i_l = \left(\frac{l}{r_p}\right)^{n_i} - \left(\frac{l-1}{r_p}\right)^{n_i}, \quad \forall i \in \{1, 2, \ldots, k\} \tag{2}$$

Now, let us turn our attention back to the estimation of the minimum number of hops $(f_p(d))$ from vehicle X with type p to the next junction point R by giving the distance between X and R as d. Obviously, in the case of $d \leqslant r_p$, the required number of hops will be equal to 1. For the other case of $d > r_p$, we will use a recursive expression of expected value to express value $f_p(d)$. Since the position of the nearest nexthop forwarder to R is unknown, we conditioned on each of the possible positions of vehicle $X^*_{V_i}$.

Note that the criterion for choosing the nexthop forwarder will simply be according to which type of nexthop forwarder candidate in C will result in the minimum hop counts to R. Moreover, when the nexthop forwarder is determined, the hop count has to be increased by 1. Concluding the above discussions, the resulting estimation value of $f_p(d)$ for vehicle X with type p will be as follows.

$$f_p(d) = \begin{cases} 1 & \text{if } d \leqslant r_p \\ \min\limits_{1 \leqslant i \leqslant k} \left\{ \sum\limits_{l=1}^{r_p} (1 + f_i(d-l)) \cdot P^i_l \right\} & \text{o.w.} \end{cases} \tag{3}$$

where $P^i_l = \left(\frac{l}{r_p}\right)^{n_i} - \left(\frac{l-1}{r_p}\right)^{n_i}, \quad \forall i \in \{1, 2, \ldots, k\}$.

3.2. The proposed routing algorithm

In this subsection, the proposed Stochastic Minimum-hops Prediction Routing (the SMPR) based on the above prediction method SMFPM is described. Due to the nearest vehicle $X^*_{V_i}$ of type i $(1 \leqslant i \leqslant k)$ to the junction point R dominating the other type i vehicles, at first, we determine the candidate set C by narrowing down the neighboring set N to the collection of each nearest vehicle $X^*_{V_i}$ of type i $(1 \leqslant i \leqslant k)$ to R, for example, the circled vehicles in Fig. 5 (in the case of $k = 2$).

Next, for each candidate vehicle $X^*_{V_i} \in C, 1 \leqslant i \leqslant k$, we let the distance between $X^*_{V_i}$ and R be d_i, we use the SMFPM to estimate the minimum number of hops $f_i(d_i)$ to R, if we choose $X^*_{V_i}$ as the nexthop forwarder, and the k estimation values $f_i(d_i)$, $1 \leqslant i \leqslant k$ will be obtained. Let vehicle $X^*_{V_{i^*}}$ have the smallest value of $f_{i^*}(d_{i^*})$ among the k values. Then, vehicle $X^*_{V_{i^*}}$ will be selected to be the nexthop forwarder and to forward every carried packet from X_{curr} to $X^*_{V_{i^*}}$. The packet relaying will be repeated hop by hop according to the above process until the next junction point R is reached. The detailed routing algorithm of SMPR is given in Fig. 6.

The proposed SMPR algorithm can assist the current carrier to select the best nexthop forwarder from its neighboring set at the

Algorithm Stochastic-Minimum-hops-Prediction-Routing;
Input:
k: the total number of vehicle types in the road segment;
p: the type number of vehicle X_{curr};
ρ_i: the population density of vehicle type i in the road segment, $\forall i \in \{1, 2, \ldots, k\}$;
r_i: the transmission range of vehicle type i, $\forall i \in \{1, 2, \ldots, k\}$;
R: the next junction point;
$L_{X_{curr}R}$: the length between X_{curr} and R;

{
/* calculate the number of vehicles and the nexthop forwarder candidate set C in the transmission range of X_{curr} */
let the candidate set $C = \emptyset$;
for (each vehicle type $i \in \{1, 2, \ldots, k\}$) do {
let the number of vehicles of type i be $n_i = \rho_i \cdot r_p$;
determine the nearest vehicle $X^*_{V_i}$ of type i in the transmission range of X_{cand} to R, and let the distance between $X^*_{V_i}$ and X_{curr} be $x^*_{V_i}$;
$d_i = L_{X_{curr}R} - x^*_{V_i}$;
$C = C \cup \{X^*_{V_i}\}$;
}
/* determine the minimum number of hops from X_{curr} to R using the vehicle $X^*_{V_i} \in C$ as the nexthop forwarder */
for (each nexthop forwarder candidate $X^*_{V_i} \in C$) do {
$f_p(d) = \{ \begin{matrix} 1 & \text{if } d \leq r_p \\ \min_{1 \leq i \leq k}\{\sum_{l=1}^{r_p}(1 + f_i(d-l)) \cdot P^i_l\} & \text{o.w.} \end{matrix}$;
where $P^i_l = (\frac{l}{r_p})^{n_i} - (\frac{l-1}{r_p})^{n_i}, \forall i \in \{1, 2, \ldots, k\}$;
}
/* routing decision and forwarding */
let i^* be the type number of the optimal nexthop forwarding vehicle such that $f_{i^*}(d_{i^*}) = \min_{1 \leq i \leq k} f_i(d_i)$;
forward the packets carrying in X_{curr} to the chosen nexthop forwarder $X_{V_{i^*}}$;

}

Fig. 6. The complete SMPR algorithm.

time of message relaying. Note that the current neighboring set is fresh and accurate at the time of decision making, while the latter will become increasingly inaccurate due to the roaming of vehicles. The SMPR algorithm adopts a stochastic approach to predict the minimum number of hops with respect to each candidate nexthop forwarder. When the best candidate vehicle is chosen, the packets will be forwarded to it. Again, the new forwarder will take its current status from the neighboring set along with the stochastic estimation for later situations to make further decisions.

4. Simulation results

In our simulations, we used the network simulator NS-2 [35] to conduct the experiments to demonstrate the performance of our proposed routing algorithm in four different scenarios. In the following, we briefly describe the simulation environment setting in Section 4.1. The comparison factors, the simulation results, and the communication overheads analysis are given in Sections 4.2, 4.3 and 4.4, respectively.

4.1. Simulation environment setting

In the simulation environment, we assume that there are two types of vehicle (that is, $k = 2$), ordinary cars (type 1 vehicle) and buses (type 2 vehicle). The size of the simulation areas is set to $3000 \times 3000\ \mathrm{m}^2$. The moving velocities of the vehicles are set to range from 10 m/s to 20 m/s, and the transmission ranges of the two types of vehicles are $r_{car} = 150$ m and $r_{bus} = 250$ m, respectively. The number of total vehicles in our simulations is given as 50, 100, 150, and 200, where the number of ordinary cars versus the number of buses is set as 4:1 (and 9:1). The two scenarios of 1 and 2 (3 and 4) consider that the number of ordinary cars versus the number of buses is set as 4:1 (and 9:1) and the transmission is set to CBR (Constant Bit Rate) and VBR (Variable Bit Rate), respectively. CBR emits fixed-size packets of 512 bytes for every 0.05 s, while VBR emits packets of a size randomly generated and ranging from 128 bytes to 512 bytes every 0.05 s. The detailed simulation settings for scenarios 1–4 are given in Table 1.

4.2. The comparison factors

In order to evaluate the performance of our proposed method against the conventional routing protocols (the AODV [27], AOMDV [24], and DSR [23]), we investigate three performance factors (the packet delivery ratio, average end-to-end delay, and the average number of hops) in the above four simulation scenarios. Each simulation instance was simulated 5 times and then we took the average of the resulting values. Each performance factor is defined as follows.

Table 1
List of parameter settings for the simulation scenarios.

Simulation scenarios	Sim1 (Sim3)	Sim2 (Sim4)
Number of nodes	50, 100, 150, 200	
Ratio between vehicle types	car:bus = 4:1 (9:1)	
Moving velocity	10–20 m/s	
Data size	CBR 512 bytes	VBR 128–512 bytes
Packet generating rate	1/0.05 packets/s	
Mobility model	Random way-point mobility	
Transmission range	car: 150 m bus: 250 m	
Simulation time	100 s	
Simulation area	$3000 \times 3000\ \mathrm{m}^2$	
MAC protocol	IEEE 802.11b	

1. **Packet delivery ratio:** The packet delivery ratio is defined as the total number of data packets successfully received by the destination ($n_{pkt_{received}}$) divided by the total number of data packets sent from the source ($n_{pkt_{send}}$). This comparison factor represents how reliable the routing protocol is. The larger the packet delivery ratio is, the more reliable the investigated routing protocol is, and vice versa. The formal definition is,

$$\text{Packet delivery ratio} = \frac{n_{pkt_{received}}}{n_{pkt_{send}}} \tag{4}$$

2. **Average end-to-end delay:** At first, we calculate the end-to-end delay with respect to each successfully received packet ($pkt^i_{received}, 1 \leqslant i \leqslant n_{pkt_{received}}$), by using the received time of packet $pkt^i_{received}$ at the destination ($t^i_{received}$) subtracted from the time sent from the source (t^i_{send}). Note that the resulting time period includes the data transmission delay, the propagation delay, the nodal processing delay, and the queuing delay at each intermediate node, the source node, and the destination node as well. We then take the average of the end-to-end delay of all successfully received packets. That is,

$$\text{Average end-to-end delay} = \frac{\sum_{\text{for each } pkt^i_{received}} (t^i_{received} - t^i_{send})}{n_{pkt_{received}}} \tag{5}$$

3. **Average number of hops:** For each successfully received packet ($pkt^i_{received}$), we use Hop_i to represent the total number of hops that it has traveled from the source node to the destination node. The average number of hops is defined as follows.

$$\text{Average number of hops} = \frac{\sum_{\text{for each } pkt^i_{received}} Hop_i}{n_{pkt_{received}}} \tag{6}$$

4.3. Simulation results

Simulation scenario 1 investigates the packet delivery ratio and the average end-to-end delay under the CBR transmission, and the environment settings follow the description in Table 1. Fig. 7 gives the packet delivery ratio comparison results. As shown in this figure, when the number of vehicles is small (for example, in the case of 50 nodes), our proposed method has slightly poorer performance (the packet delivery ratio) than the DSR. However, our proposed routing method SMPR outperforms the other three conventional

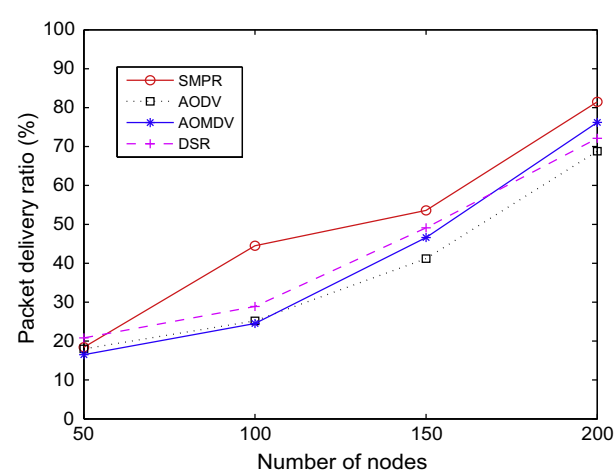

Fig. 7. The packet delivery ratio comparisons in simulation scenario 1 with CBR transmission.

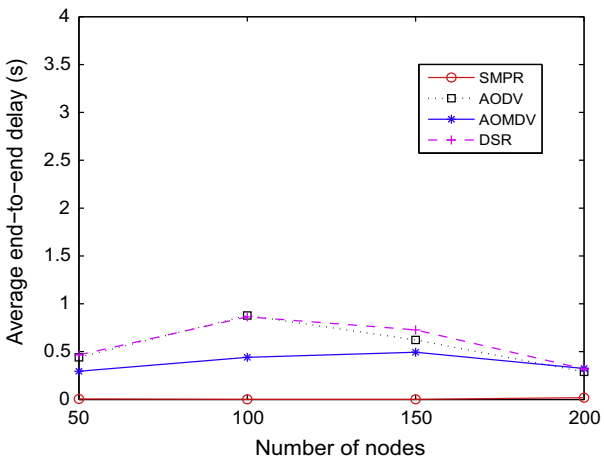

Fig. 8. The average end-to-end delay comparisons in simulation scenario 1 with CBR transmission.

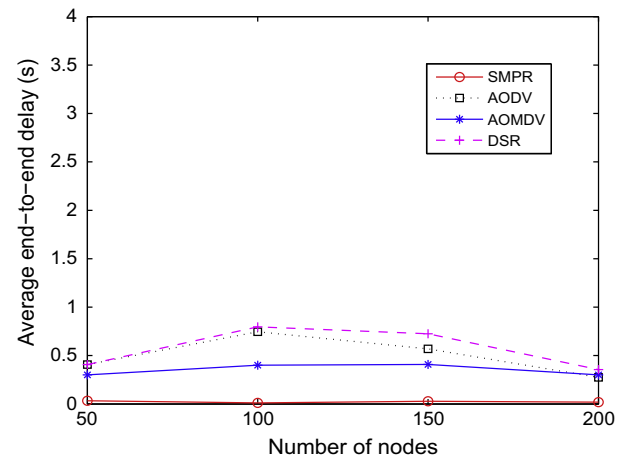

Fig. 10. The average end-to-end delay comparisons in simulation scenario 2 with VBR transmission.

routing protocols (the AODV, AOMDV, and DSR) as the number of vehicles increases. The results also show that the AODV routing protocols have the worst performance results in simulation scenario 1 when the number of vehicles is greater than 100.

The performance results for the average end-to-end delay comparisons are given in Fig. 8. Our proposed method SMPR also outperformed the other conventional routing protocols as the number of vehicle nodes varied, which means it uses less time to deliver the packets compared to the other methods. In this figure, the routing protocol DSR has the worst performance results. Figs. 9 and 10 shown the simulation results under the VBR transmission of simulation scenario 2 for the packet delivery ratio and the average end-to-end delay, respectively. These figures also show similar performance results as in simulation scenario 1. We also conducted simulation scenarios 3 and 4 for the cases of the number of ordinary cars versus the number of buses set as 9:1. Figs. 11 and 12 (Figs. 13 and 14) show the simulation results under the CBR (and VBR) transmission of simulation scenario 3 (and 4) for the packet delivery ratio and the average end-to-end delay, respectively. These figures also give similar performance results as in simulation scenarios 1 and 2.

Finally, we investigate the average number of hops required to relay the packet from the source to the destination. The compared methods include the $SMPR_{best}$, the $SMPR_{bus}$, and the $SMPR_{car}$. Note

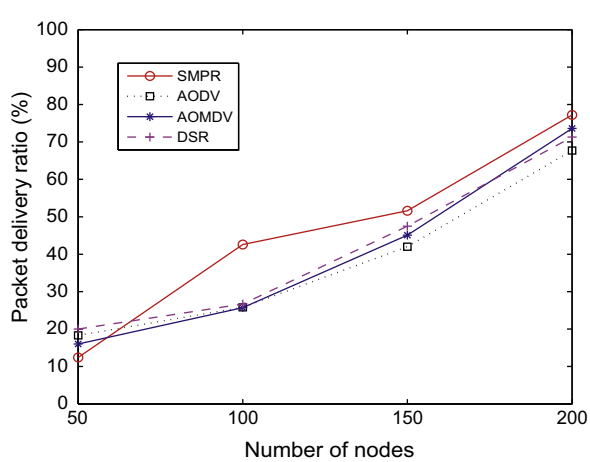

Fig. 9. The packet delivery ratio comparisons in simulation scenario 2 with VBR transmission.

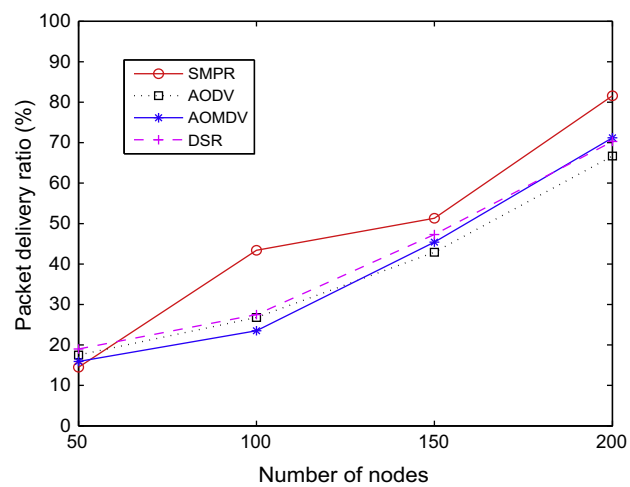

Fig. 11. The packet delivery ratio comparisons in simulation scenario 3 with CBR transmission.

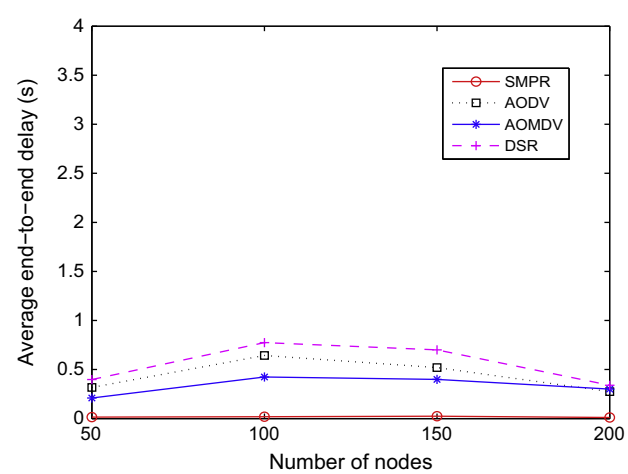

Fig. 12. The average end-to-end delay comparisons in simulation scenario 3 with CBR transmission.

that, in the case of the nexthop candidate vehicle of type bus (and car) not existing in the candidate set, then the method will use the other type of candidate vehicle instead. All these compared

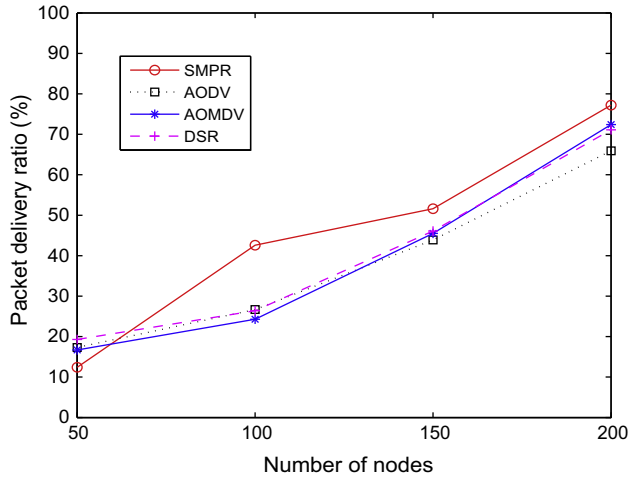

Fig. 13. The packet delivery ratio comparisons in simulation scenario 4 with VBR transmission.

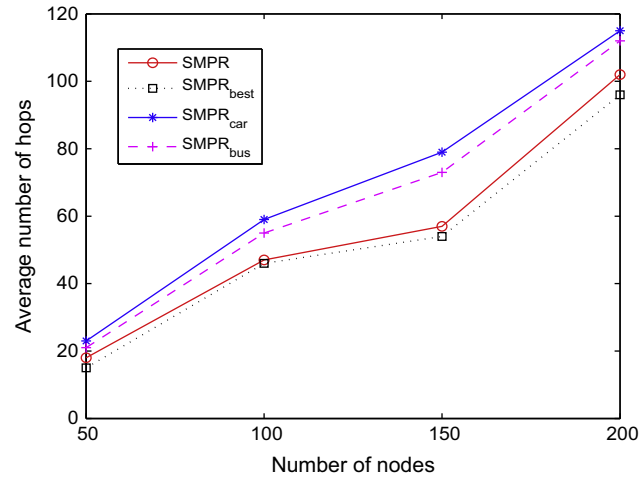

Fig. 15. The average number of hops comparisons in simulation scenario 1 with CBR transmission.

methods are based on the proposed SMPR method with some modifications. For the $SMPR_{best}$, it estimates the minimum number of hops from the source to the destination according to the realistic environment status (which includes the exact position of each vehicle) at the current time. The routing method $SMPR_{bus}$ (and $SMPR_{car}$) always depicts the nexthop forwarder from buses (and cars) at each nexthop forwarding decision occurrence.

Fig. 15 gives the comparison results for simulation scenario 1. As shown in this figure, there is no doubt that the method $SMPR_{best}$ always routes the packets with the optimum number of hops. Our proposed method of SMPR is very close to the performance curve of the $SMPR_{best}$ in each simulation case when the number of nodes varies. This is because the proposed SMPR will choose the vehicle with the smallest predicted number of hops to be the nexthop forwarder; thus the forwarding path may consist of different types of vehicles. The other two methods, $SMPR_{bus}$ and $SMPR_{car}$ use a greater number of hops compared with our proposed SMPR method.

4.4. Communication overheads analysis

Now, let us turn our attention to the analysis of the communication overheads of our proposed SMPR method. Obviously, the communication overheads for refreshing the population densities with respect to a road segment will be triple the number of vehicles on the road segment (that is, the broadcasting of request messages plus the response messages and also the dissemination of the computing results). Note that the above communication overheads depend on the frequency of refreshing. The communication overheads of uncasting from a source node to a destination node are discussed as follows. Recall that the process of collecting the required information to perform the nexthop forwarder selection of a current carrier is an on-demand approach; that is, whenever a vehicle is designated as the current carrier, it then broadcasts a request message to its one-hop neighbors asking them to send back their positions and the vehicle type numbers. And then, to determine the new nexthop forwarder, the above operations will be performed on each nexthop forwarder in the routing path from the source node to the destination node. Let the number of hops from the source to the destination be *HOP*, the population density (and the transmission range) of vehicle type i be ρ_i (and r_i), $1 \leqslant i \leqslant k$, respectively, and let $\rho\ (= \sum_{i=1}^{k} \rho_i)$ be the population density of all vehicles on a road segment. Thus the communication overheads in terms of the number of packets sent will be equal to,

$$\sum_{i=1}^{HOP}\left(1+\left(\sum_{j=1}^{k}\rho_j\right)\cdot r_{i_t}\right), \quad \text{where } i_t \text{ denotes the vehicle type of the } i \text{ th hop of the forwarder.} \tag{7}$$

Note that, in the above equation, the value 1 (and $\left(\sum_{j=1}^{k}\rho_j\right)\cdot r_{i_t}$) is equal to the number of request messages (and response messages) sent from (and received by) the ith hop of the forwarder. Let $r_{\max} = \max_{1\leqslant i\leqslant k} r_i$. Then we have that

$$\sum_{i=1}^{HOP}\left(1+\left(\sum_{j=1}^{k}\rho_j\right)\cdot r_{i_t}\right) \leqslant \sum_{i=1}^{HOP}(1+\rho\cdot r_{\max}) = Hop\cdot(1+\rho\cdot r_{\max}) \tag{8}$$

Therefore, the upper bound of the communication overheads for message relaying by our proposed SMPR method is equal to $Hop\cdot(1+\rho\cdot r_{\max})$, which is proportional to the hop counts of the communication path. Since the number of hops of our proposed method is very close to the optimum number of hops (see the simulation results shown in Fig. 15) and its on-demand property, the communication overheads of our proposed SMPR method are limited.

Summarizing the above numerical and computational analysis, our proposed SMPR algorithm outperformed the conventional algorithms (AODV, AOMDV, and DSR) on the comparisons of packet delivery ratio and average end-to-end delay in the VANETs

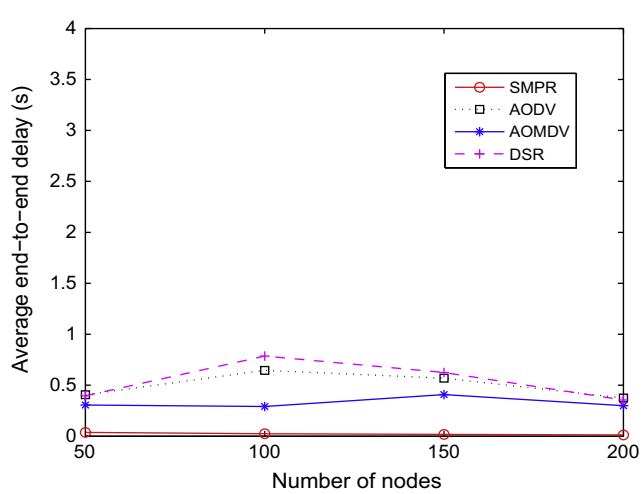

Fig. 14. The average end-to-end delay comparisons in simulation scenario 4 with VBR transmission.

heterogeneous transmission range environment. The simulation analysis of the number of hops between source and destination comparison also shows that the SMPR algorithm can automatically select the route consisting of buses and ordinary cars with shorter path lengths than the homogeneous transmission range environment of VANETs. In addition, the communication overheads analysis also demonstrates that the SMPR algorithm uses only a limited number of packets for the communication overheads. Therefore, the proposed algorithm is a competitive routing algorithm for the case of a VANETs environment with a heterogeneous transmission range.

5. Conclusion

In a VANETs environment, directly applying the traditional routing protocols will result in poor performance. Therefore, designing suitable routing protocols for such environments is an emerging area of research. Generally, vehicles equipped with heterogeneous wireless network interfaces can improve the quality of transmission and gain a good signal while relocating. Moreover, it can also gain the merit of parallel network channel transmission to enhance the routing performance. Thus the heterogeneous vehicle networks are likely to become increasingly popular in the near future. In this paper, we propose a greedy forwarding approach for VANETs with heterogeneous types of vehicles. A method called the SMFPM is proposed to estimate the minimum number of hops required from a vehicle to the next junction point. Based on this estimation method, a routing protocol called the SMPR for VANETs is also developed. The simulation results show that our proposed routing protocol SMPR outperformed the other compared routing protocols in the CBR and VBR packet transmission scenarios in terms of the packet delivery ratio and the average end-to-end delay comparisons. Besides, the simulation results also show that the average number of hops required to transmit a packet from the source to the destination by our proposed routing method is very close to the performance of the optimum method. The computational analysis also demonstrates that the communication overheads of the SMPR are less.

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