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FUZZY LOGIC-ASSISTED GEOGRAPHICAL ROUTING OVER VEHICULAR AD HOC NETWORKS

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Abstract. *Vehicular Ad Hoc Networks (VANETs) is a type of ad hoc network that allows vehicles to communicate with each other in the absence of fixed infrastructure. Inter-vehicle geographic routing has been proven to perform well in high speed vehicular environments. In connected and reliable vehicular scenarios, greedy based geographical routing protocols could forward data packets efficiently and quickly towards the destination. However, extremely dynamic vehicular environments and uneven distribution of vehicles could create unreliable wireless channels between vehicles and disconnected vehicular partitions. On the one hand, in connected vehicular networks, an intelligent multi-metric routing protocol must be exploited in consideration of the unreliable nature of wireless channels between vehicles and vehicular mobility characteristics. On the other hand, a mechanism must be utilized to create a virtual bridge between vehicles in disconnected vehicular scenarios. To this end, we firstly propose a novel Stability and Reliability aware Routing (SRR) protocol that forwards packets with a high degree of reliability and stability towards the destination. That is, the SRR protocol incorporates fuzzy logic with geographical routing when making packet forwarding decisions. Routing metrics, such as direction and distance, are considered as inputs of the fuzzy decision making system so that the best preferable neighbour around a smart vehicle is selected. We then utilize a mechanism to cache data packets once the network is disconnected and then switch back to SRR in a connected vehicular scenario. Traffic density is considered as an input when estimating network dis-connectivity. After developing an analytical model of our protocol, we implemented it and compared it with standard protocols. In a realistic highway vehicular scenario, the results show that the proposed protocol performs better than Greedy Perimeter Coordinator Routing (GPCR) with increases of up to 21.12 %, 29.34 % and 3.98 % in packet delivery ratio in high lossy channel, sparse, and dense traffic conditions respectively. In terms of average packet delay, SRR performs better with performance increases of up to 23.92 % in dense traffic conditions. But, GPCR performs better in sparse traffic conditions by up to 36.30 %. Finally, SRR has less control overhead than the state of the art protocols.*

Keywords: Vehicular ad hoc networks, Fuzzy logic, Packet caching, Geographical routing, Reliability, Stability

1. **Introduction.** Recently, the growth in the number of vehicles on the road has put great stress on transportation systems. This abrupt growth of vehicles has made driving unsafe and hazardous. Thus, existing transportation infrastructure requires improvements

in traffic safety and efficiency. To accomplish this, Intelligent Transportation Systems (ITS) have been considered to enable such diverse traffic applications as traffic safety, cooperative traffic monitoring and control of traffic flow. These traffic applications would become realities through the emergence of VANET because it is considered as a network environment of ITS. In addition, in the near future, more vehicles will be embedded with devices that facilitate communication between vehicles, such as Wireless Access in Vehicular Environment (WAVE) [1]. When vehicles are equipped with WAVE, they can communicate with nearby cars and access points within their coverage area. Since vehicles have limited short radio range, they cannot cover large scale areas unless they use multi-hop routing protocols, which is a significant handing over from traffic safety applications that require short distance coverage to wide area coverage.

However, designing a geographical multi-hop routing protocol which considers vehicular mobility characteristics along with the quality of inter-vehicle wireless channels is a challenging task. This is due to frequent topology fragmentation between vehicles as well as the high mobility of vehicles, which are constrained by roads. Further, the communication channel between vehicles is susceptible to packet errors and log-normal shadowing together with different types of fading. Under these conditions, existing protocols designed for Mobile Ad hoc Networks (MANET), Ad hoc On Demand Distance Vector (AODV) [2]; Dynamic Source Routing (DSR) [3], cannot be applied straight-away on VANET. The majority of existing routing protocols developed for VANET are based on geography rather than topology. These kinds of routing protocols relay data packets by considering the position of the destination. Further, Geographic routing is more desirable for the following reasons. First, in the near future, vehicles will be embedded with Global Positioning System (GPS) and navigation systems, hence geographical routing achieves monumental success in VANET. Second, it does not maintain established routes between source and destination; thus, it is less susceptible to route overhead.

In vehicular wireless networks, the performance of existing geographical routing protocols, such as [4, 5, 6, 7, 8], has been improved by taking into consideration efficient forwarding strategies and vehicular mobility characteristics. However, each of the aforementioned routing protocols has its own limitations. Greedy Position Stateless Routing (GPSR) [4] may not perform well because of uneven traffic distribution – a combination of dense and sparse traffic conditions along different road segments. Under these circumstances, GPSR activates face routing, in which a data packet is forwarded on a series of faces towards the destination. Based on the assumption that road traffic is planar graph, some authors proposed Greedy Perimeter Coordinator Routing (GPCR) [5] which utilizes the concept of junction nodes to control the next road segments that packets should follow. However, the idea of junction nodes is an issue and hard to maintain. The authors in [6] developed Anchor-based Street and Traffic Aware Routing (A-STAR) to utilize bus route information to discover the best anchor paths of higher connectivity toward the packet's destination. However, this mechanism involves routing the packet forward along the anchor path, which may not be the best routing path, potentially leading to higher delay. Furthermore, J. Gong et al. proposed Predictive Directional Greedy Routing (PDGR) [7] to efficiently forward data packets to the best preferable node based on both mobility and future mobility characteristics. However, they did not consider the unreliable nature of wireless channels as well as the dis-connectivity of a packet carrier node with its neighbours. B. Jarupan et al. in [8] proposed a cross layer location based communication protocol for delay-aware in vehicular access networks. The proposed routing protocol produces good performance in terms of end-to-end delay and packet success rates. However, their proposal is formulated based on ideal wireless channels between vehicles.

All of the aforementioned routing protocols consider ideal wireless channels rather than realistic error prone channels between vehicles due to log-normal shadowing and types of fading. Moreover, some of the geographical routing protocols greedily nominate the node which is the shortest distance to the specified packet destination. The drawback of this packet forwarding mechanism is that, when the distance between the packet source and the next packet forwarder increases, the degree of attenuation of the transmitted signal also increases. It is a well known fact that signal loss becomes higher over longer distances and is the cause of higher attenuation. As a result, two things happen: the network suffers in terms of successful packet delivery rates and the control overhead profoundly increases. In addition, almost all of the above routing protocols fail to combine geographical routing in connected networks with data packet forwarding in disconnected partitions. In other words, these protocols cannot adapt to uneven traffic conditions.

Based on the brief discussion as explained above, it is clear that the distance between source and relay nodes, as well as vehicular mobility characteristics, are two prominent parameters of the route selection process for multi-hop routing over vehicular scenario. Vehicular traffic density is also counted as an important parameter for cognition the dis-connectivity of the vehicular scenarios. In this study, we firstly propose a new Stability and Reliability aware Routing (SRR) protocol that forwards packets with high reliability and stability towards destinations. That is, the SRR protocol incorporates fuzzy logic with geographical routing in order to lend cognitive capability to packet forwarding decisions. Routing metrics, including direction and distance, are considered inputs of the fuzzy decision making system in order to select the best preferable route around a smart vehicle. The decision is based on distance as well as relative direction between vehicles for the following reasons: relative distance quantifies the severity of signal attenuation with respect to distance, whereas direction of movement helps to increase connectivity between vehicles and packet forwarding progress towards destinations. We propose a local decision mechanism to observe the network partitions in order to allow switching from SRR mode to queuing mode or vice versa. Furthermore, we then utilize the idea of carry-and-forward mechanism to tackle network dis-connectivity; that is, when a vehicle encounters network dis-connectivity, it continues to carry packets rather than simply dropping them. In this mechanism, traffic density is considered as an input to estimate network dis-connectivity. The proposed routing protocol has been analytically modeled and simulated using JiST/SWANs [9] simulation tools for performance evaluation. Likewise, the fuzzy logic-based forwarding decision algorithm which is integrated into the SRR protocol is implemented in Java language. It is noteworthy that our proposed multi-hop geographical routing protocol is well suited for many applications. For instance, in comfort-related applications, it can be used for chatting, gaming, file sharing or infotainment between vehicles. We distill and summarize the contributions of this study as follows:

- Considering the fact that lossy wireless channels lead to signal attenuation, in contrast to all routing protocols, the decision mechanism of the proposed fuzzy algorithm takes into account the distance between the source and different neighbour nodes as an input to the fuzzy in order to make forwarding more reliable.
- Since single metric routing does not forward data packets to best preferable relay node, a novel multi-metric geographic routing protocol has been proposed. The proposed SRR protocol intelligently combines distance between vehicles and the direction of vehicles towards destination.

- In order to tackle data packet loss (queue up data packets) in a disconnected vehicular scenario, a mechanism has been developed to bridge the gap between dis-connected and connected vehicular networks.
- We develop an analytical model for the switching probabilities between connected and dis-connected vehicular traffic scenarios.

The rest of the paper is arranged as follows. Section 2 provides an overview of the current state of the art. The proposed SRR protocol, tackling dis-connectivity mechanisms and the designed fuzzy inference system are discussed in Section 3. In Section 4, we develop and discuss the analytical model to compute the switching probabilities. This is followed by performance validation and evaluation in Section 5, where we highlight the feasibility of our protocol by considering a realistic (curvature) highway vehicular scenario and realistic wireless channels. Finally, Section 6 concludes the paper and recommends future directions.

2. **Related Work.**

In this section, we briefly describe the recent routing protocols used in VANET, notably geographic routing and fuzzy decision based routing protocols. This is because SRR protocol is the result of the integration of geographical routing and fuzzy logic system.

2.1. **Geographical and fuzzy based routing.**

2.1.1. *Greedy perimeter stateless routing.* Greedy Perimeter Stateless Routing (GPSR) [4] is considered to be position based routing because it utilizes the positions of the vehicles and the location of the packet's destination when making forwarding decisions. In addition, the GPSR protocol is known as stateless, because the intermediate vehicles employ the hello packet to collect the positions of their neighbouring vehicles rather than using routing metrics. GPSR forwards packets in two modes: greedy mode and perimeter mode.

In greedy mode, an intermediate node receives a packet, then selects a neighbour node that is geographically closest to the destination node. If an intermediate node has no other neighbours closer to the destination than itself, it enters a local optimum. In this case, the packet will switch to the perimeter mode to recover from the local optimum. The GPSRs perimeter mode relays data packets by utilizing the right hand rule with respect to the starting vector constraint. For instance, when a packet at intermediate node x switches to the perimeter mode, it draws a vector from node x to the destination. Node x then forwards the packet to the first edge counter clockwise about x from the vector. GPSR protocol does not take these features into consideration since vehicular networks have unique mobility characteristics, unreliable wireless channels and frequent network fragmentation.

2.1.2. *Greedy perimeter coordinator routing (GPCR)* [5]. It is impractical to create planar graphs in GPSR protocol since vehicular traffic density is highly variable with space and time. To tackle the planarization problem, Lochert et al. designed GPCR [5]. The GPCR protocol solves the planarization problem by considering urban streets as a planar graph. Each road segment represents an edge of the network topology graph, and the road junctions represent the vertices. In GPCR, the intermediate nodes greedily forward packets towards the destination until it enters the junction node. The junction node then selects the neighbour node which is closer to the destination. In the perimeter mode, the road junction vehicles relay data packets to the next hop by utilizing the right-hand rule. This routing protocol solves the problem of planarization. However, it does not consider lossy wireless channels between vehicles and frequent topology holes between platoons of vehicles.

2.1.3. *Anchor-based street and traffic aware routing (A-STAR)* [6]. This protocol provides end-to-end connection between vehicles in sparse vehicular scenarios. The information garnered from city bus paths has been used to find the best anchor path with high packet delivery. This anchor path guarantees end to end delivery even in low vehicular traffic densities. When a packet reaches a local optimum, it switches to recovery mode by finding new anchor paths towards the packet destination. The simulation based study has proven its superiority in comparison with GSR and GPSR. However, since the routing path follows the anchor path, it may not be optimal. As a result, it leads to large route delay.

2.1.4. *Location-delay-aware cross layer communication 2009 (LD-CROP).* B. Jarupan et al. in [8] proposed (LD-CROP). This protocol uses the concept of cross layer communication between data link layers and routing functions in the network layer. The data link layer is utilized to gather local traffic statistics through monitoring channel conditions. After that, the network layer fetches the local traffic statistics to elect the preferable available path based on delay estimation model. The simulation based study displays the superiority of LD-CROP in terms of latency and successful packet rates when compared with DSR [3] and Vehicle Assisted Data Delivery (VADD) [10]. Y. S. Chen et al. in [11] proposed mobicast protocol for supporting applications which require "spatiotemporal" coordination in VANETs. However, they (mobicast and LD-CROP) consider ideal wireless channel between vehicles. Moreover, they do not consider the dis-connectivity variation with space and time in vehicular scenarios.

2.1.5. *Fuzzy logic and optimized fuzzy logic based path selection.* C.-J. Huang et al. in [12] proposed a load balancing and congestion avoidance routing mechanism over short radio ranges to guarantee the Quality of Service (QoS) requirements of real time traffic. A fuzzy logic decision making system is utilized to select the intermediate nodes on the routing path through inter-vehicle communication. The simulation based study revealed that the proposed mechanism obviously achieves excellent performance in highway traffic scenarios. While this mechanism has been developed to deal with load balancing and congestion avoidance issues, it does not take into consideration unreliable wireless channels and dis-connectivity issues in VANET. In addition, the authors in [13] proposed Fuzzy control based AODV routing (Fcar) for highway vehicular scenarios. The designed protocols used the percentage of directional vehicles and route lifetimes as routing metrics for rebroadcasting decision making processes. However, since topology based routing protocols [2, 3] are less preferable in high speed environments (due to high protocol overhead), these routing protocols embed fuzzy decision making systems with topology based routing.

3. **Protocol Overview.** The designed SRR protocol is adopted for Vehicle to Vehicle (V2V) communication systems in which vehicles communicate without the benefit of infrastructure. The protocol is used to transmit information from the source to the destination vehicle through multi-hop communication. Wireless radio communication devices are embedded into all Vehicles in order to facilitate multi-hop communications. Similar to existing works on VANET, we assume that vehicles are equipped with a GPS receiver that provides the vehicles current position to all neighbours. All vehicles are embedded with digital road maps which provide the accurate location of roads. In this article, we assume that the location discovery as provided by GPS is highly precise. Since GPS error resolution is typically within 15 meters, this assumption is fair [14]. In our protocol, a vehicle can observe its neighbours position and direction information by periodically broadcasting hello packets to vehicles within its communication range. This process increases the horizon and level of awareness between vehicles in the vicinity zone. Furthermore, we use vehicle and node interchangeably hereafter.

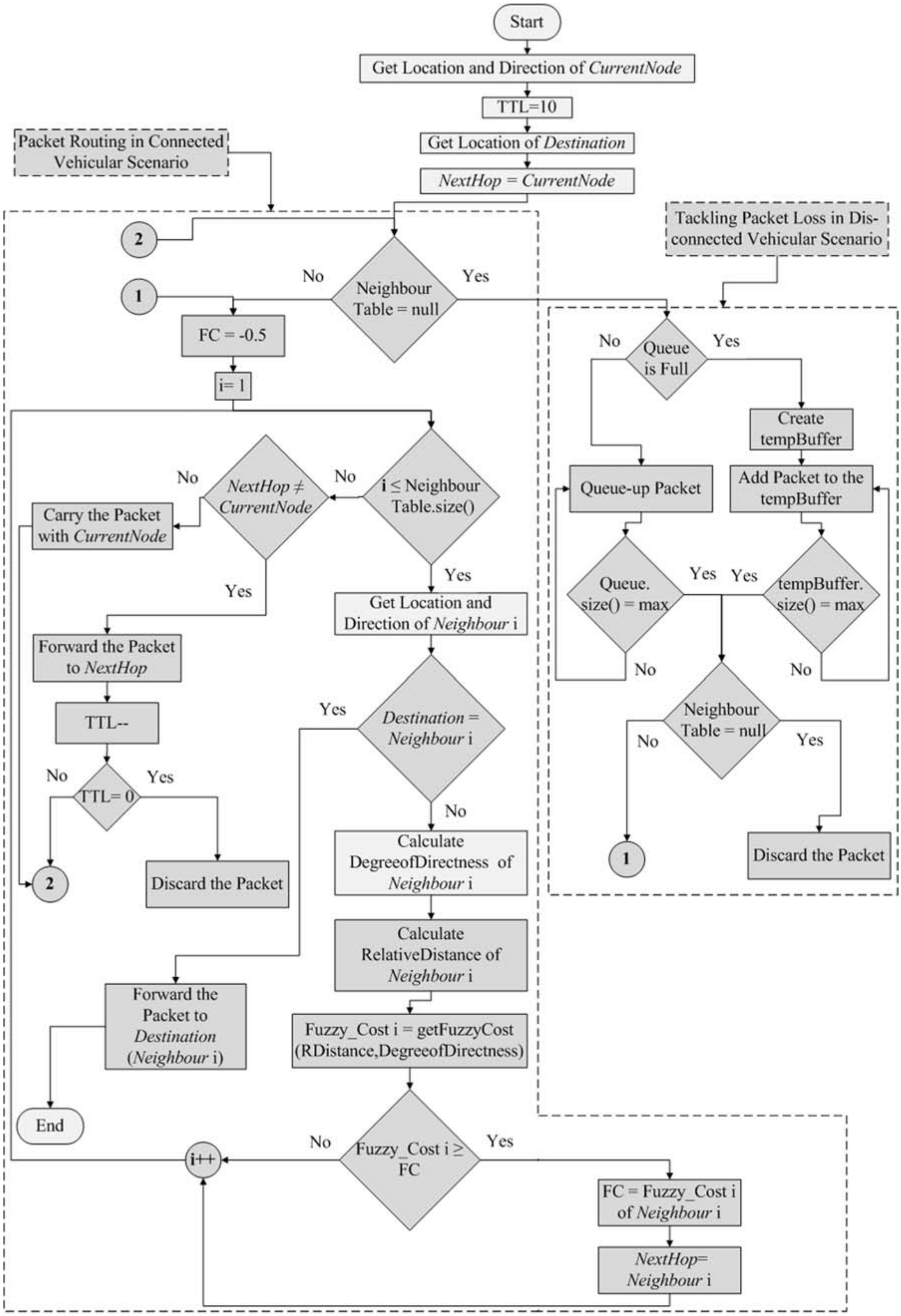
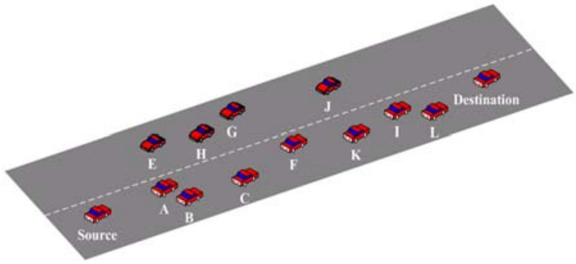
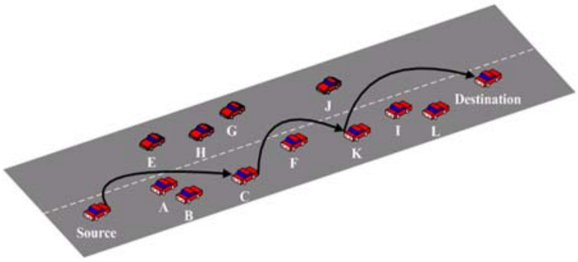


FIGURE 1. Flowchart steps of the proposed SRR protocol, dark gray blocks are the contributions of the proposed protocol



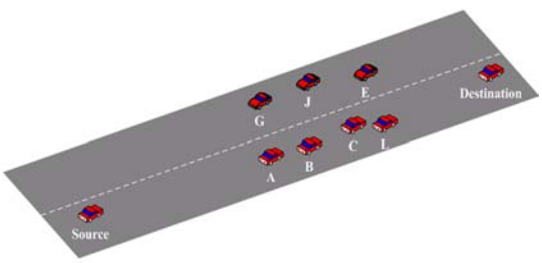
(a) A source node uses our SRR protocol to rank neighbour nodes within its radio coverage



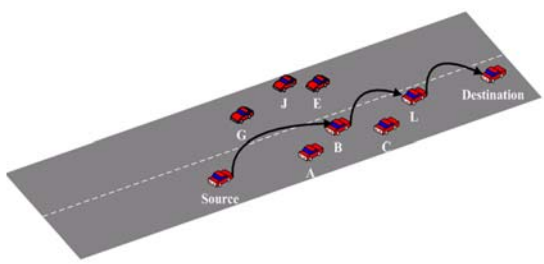
(b) A source node selects an optimal route based on the developed SRR protocol

FIGURE 2. Demonstration of SRR protocol in connected vehicular scenario

Figure 1 shows the contributions of the proposed SRR protocol which is highlighted in dark gray blocks. It can be observed that a packet carrier node (*CurrentNode*) intends to route data packets toward the destination and handles two modes of vehicular traffic density. The first, which is called packet routing in dense vehicular environment, is when vehicles are fully connected and the packet carrier node route data packets toward the packet's destination using SRR protocol. The second, when vehicles are disconnected in the vehicular environment, it does not simply drop the packet; rather, it queues it up for another forwarding opportunity. For the former mode, the packet carrier node first checks if there is at least one neighbour node (*Neighbour*) in its neighbour table. If it is not empty, the node first determines whether the destination (*Destination*) is included in the neighbour table. If one of the neighbours is a destination, the packet is forwarded to the destination. In case the destination is not in the neighbour table, the packet carrier node calculates the direction, distance and fuzzy cost of neighbour vehicles within its radio coverage. After this procedure, the packet carrier node selects the best preferable

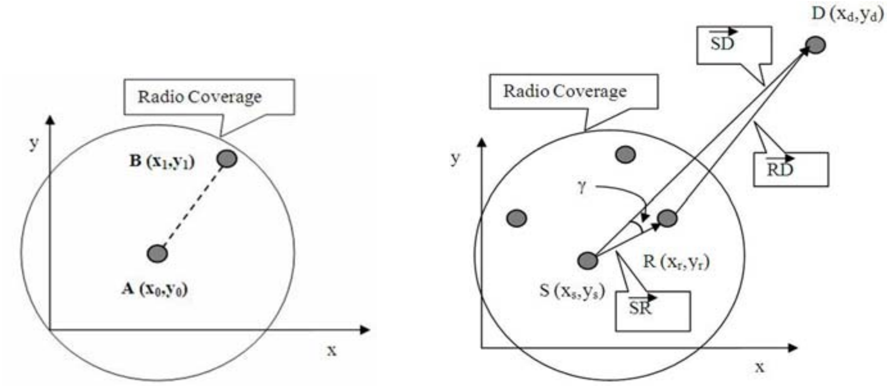


(a) A source node uses carry-and-forward mechanism to keep packets in unconnected wireless links



(b) A source node switches to SRR protocol when a vehicle has been found within its radio range

FIGURE 3. Demonstration of SRR protocol in unconnected vehicular scenario



(a) Distance calculation between packet carrier and its neighbour node

(b) Relative direction between packet carrier node and the destination node

FIGURE 4. Routing metrics

neighbour (*NextHop*) which has the highest fuzzy cost. We demonstrate packet routing in dense vehicular scenario using Figure 2. The source vehicle uses fuzzy inference system to rank neighbour nodes A, B, C, E, H, G, F within its radio coverage (Figure 2(a)). After this ranking process, the source node selects vehicle C because it offers more directionality to the destination and mid-distant to the packet carrier node (Figure 2(b)). This process will continue until the forwarded packet reaches destination.

For the latter mode, which is called tackling network dis-connectivity in Figure 1, whenever a vehicle has/received data packets and a link to the neighbour nodes is unobtainable (dis-connected network), it caches the data packet rather than simply dropping it (bridging the gap between connected and dis-connected vehicular scenarios). Figure 3(a) shows the heterogeneity of the traffic distribution in vehicular environments. As can be seen, there is a topology hole between the source node and the other platoon of vehicles. In this scenario, the source retains the data packets for other forwarding opportunities. As illustrated in Figure 3(b), in this routing opportunity, the source node switches to SRR mode and selects vehicle B as a relay node. In this way, our proposed protocol handles heterogeneous traffic distribution of vehicular networks.

3.1. **Routing metrics.** As mentioned earlier, VANET is known as a highly dynamic mobile network with unique mobility characteristics. In this environment, route decisions based on a specific metric may lead to suboptimal route selection due to several factors which may affect the quality of the route. For instance, the direction of neighbour vehicles with respect to the direction of destination is an important metric to increase the stability of the route toward destination. Likewise, the distance between the packet source and its neighbours also has a crucial impact on the selection of a reliable neighbour vehicle within its radio range. In the following sections, the routing metrics are explained.

3.1.1. *Tracking distance.* In the radio range of a vehicle, there is the possibility that two nodes are very close to each other, or they are separated by a distance which is close to the maximum radio range. Neither the former nor the latter case is desirable. It is a well known fact that a shorter distance between nodes leads to high number of hops. Furthermore, nearest nodes from the source could generate higher interference [15]. On the other hand, when the source selects a node that is close to maximum radio communication range, the probability of link failure increases due to high signal attenuation of unreliable wireless channels [16, 17, 18]. Also, due to staleness of the neighbour lists, the probability of the outermost nodes exiting from the radio range before receiving their data packets is higher. The SRR protocol tackles this issue by giving priority to the node/nodes that establish mid-distance to the packet carrier node. This priority restriction significantly increases the reliability of packet forwarding under error prone wireless channels. More precisely, reliability increases in the sense that a mid-distant node has more opportunities to forward data packets compared with an outermost node. As witnessed by Lee et al. (2010) longer distance from the source may lead to higher packet error in the wireless channels between vehicles. Since the position of vehicles is known via GPS, the Pythagoras theorem (Equation (1)) is used to determine distance between two nodes (Figure 4(a)).

$$D = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \tag{1}$$

3.1.2. *Tracking of relative direction.* In the previous subsection, the importance of distance based forwarding has been illustrated. Likewise, the direction of movement of the vehicles facilitates stable packet forwarding towards the destination. This is because the direction of vehicles is constrained by the roads. On a straight highway, vehicles are travelling in the same or opposite directions. However, in realistic highway scenarios (highway with curvature), the direction vector of vehicles is not always parallel to each other. Thus, we place a great deal of reliance on this feature to select stable routes towards destinations. In our protocol, vehicles are knowledgeable about their direction as well as their neighbours direction of movement. For instance, when vehicle A intends to route data packets towards its destination, it sends the packet to its more directional neighbour node in the direction of the destination (Figure 4(b)).

Direction based packet forwarding is demonstrated in Figure 4(b), where the arrow headed lines represent the directions of the source and its neighbour vehicles towards destination. The source S calculates the angle $\gamma = \angle DSR$ that is made between the vectors $\vec{SR}$ and $\vec{SD}$. After calculating the angle of neighbours, the probability of the vehicle with the (smallest angle) highest directionality towards the packet's destination is selected to forward the packets. The selection procedure would continue as mentioned until packets are received at destination. Furthermore, the derivation of angle γ is depicted below [19]:

$$\vec{SR} = \langle (x_r - x_s), (y_r - y_s) \rangle \tag{2}$$

$$\vec{RD} = \langle (x_d - x_r), (y_d - y_r) \rangle \tag{3}$$

$$\vec{SD} = \langle (x_d - x_s), (y_d - y_s) \rangle \tag{4}$$

Then the angle between two vectors becomes:

$$\cos\gamma = \frac{\vec{SR} \cdot \vec{SD}}{|\vec{SR}| \cdot |\vec{SD}|} \tag{5}$$

In this way, packet carrier vehicles could determine the information regarding relative direction of vehicles as well as distance between vehicles. This information is ready for an intelligent decision making system that is discussed in the next section.

3.2. **Design of fuzzy logic decision making system.** As stated earlier, due to the odd characteristics of VANET many criteria should be considered when selecting best preferable neighbour node. Fuzzy logic systems are able to make reasonable decisions based on input membership functions and a group of fuzzy rules similar to the way the human brain operates, in which the brain simulates the interpretation of uncertain afferent information [20]. Fuzzy logic based mechanisms perform well in decision making systems, control, estimation and prediction processes. In light of these fuzzy logic applications, it has been applied in this article to elect the preferable neighbour node, based

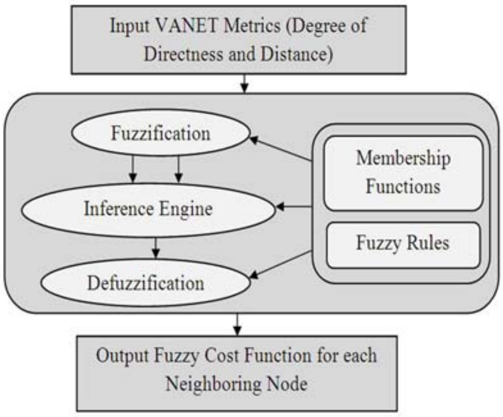


FIGURE 5. Computation of fuzzy cost when packet carrier node forward packets

on intelligently combined metrics. In this case, the source does not know which neighbour node is the best, so fuzzy is the answer to this uncertain type of problem.

Figure 5 depicts the components of a fuzzy inference system which is composed of fuzzification, knowledge rule base, and defuzzification. The first step in designing a fuzzy inference system is to determine the shape and range of membership functions to the input and output fuzzy variables. After the determination of membership functions, an inference engine should be developed to build a fuzzy inference system. Furthermore, a group of rules is used to represent inference engines to estimate the control action in linguistic form. The overall fuzzy logic process involved in electing the best preferable neighbour node (in a distribute way) is demonstrated as follows:

3.2.1. *Fuzzification of inputs and outputs.* The two input routing metrics to be fuzzified are relative direction and distance values (Figure 6). The membership functions named *Less Directed*, *Mid Directed* and *More Directed* are used to represent the *Degree of Directness*. The determination of *Degree of Directness* membership functions can be obtained based on experience as well as trial and error of the application requirement; thus the range is between (-1) to (1). This is because the range of $\cos\sigma$ is between -1 to 1 (Equation (5)). The minimum value (-1) of Degree of Directness represents the fact that neighbour nodes are directed less towards destination while it is maximum value illustrates high directionality towards destination. When the vehicles are travelling on the roads, the value of $\cos\sigma$ changes between (-1) to (1). Therefore, when a packet carrier node has data packets for transmission, it gives higher rank to a vehicle with high directionality towards destination.

Similarly, we can also determine the membership functions of the *Distance* variable, which are *Far*, *Intermediate* and *Close*. After that, we assign the normalized range, which represents the range of membership functions from (0.05) to (0.96) (Figure 6). The normalized values of distance could be calculated as follows:

$$RDistance = 1 - \frac{D}{R} \tag{6}$$

where D is the distance as determined by Equation (1) and R is a radio communication range.

The output fuzzy cost function ranges between (-0.5) to (0.5). The greater this value, the higher the probability of selecting a specified neighbour node. However, in cases where more than one neighbour node has the same score, the packet carrier node randomly selects one of them. In addition, since the triangular membership function has a simple formula

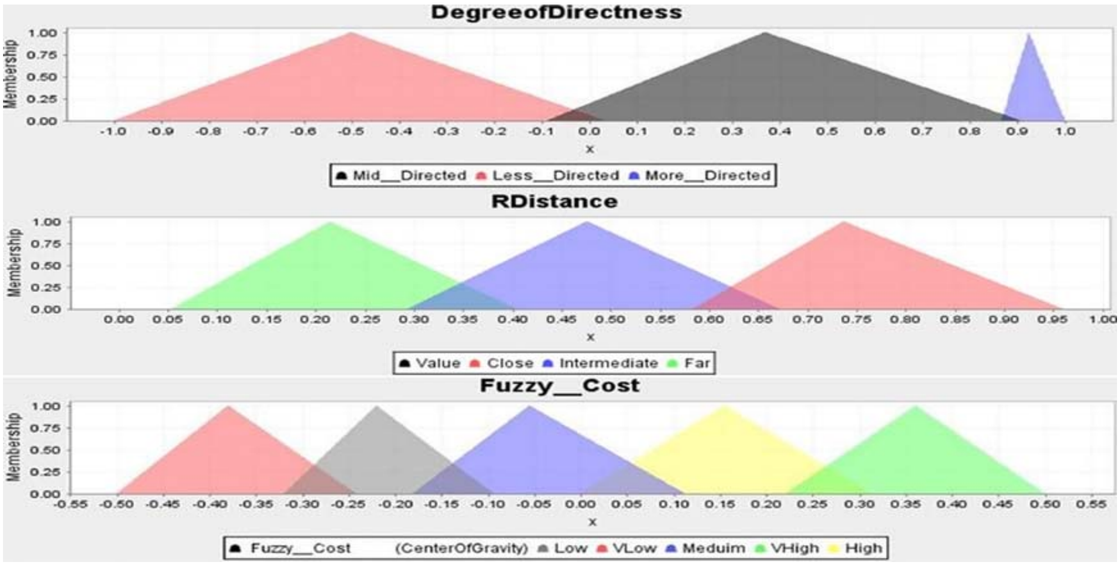


Figure 6. Fuzzy membership functions for DegreeofDirectness, RDistance and FuzzyCost

and low computation overhead, it has been extensively used in real-time applications. Therefore, we also use this type of membership function in the design of a fuzzy inference system. It is noteworthy to mention that the wise design of membership function has a positive impact on the performance of fuzzy decision making.

3.2.2. *Fuzzy inference engine.* The brain of the fuzzy inference system consists of a group of IF-THEN rules used to infer output values. We have designed the inference engine to connect the inputs and outputs based on a careful understanding of the philosophy behind routing metrics and vehicular networks behaviour. The fuzzy logic inference is designed based on 9 rules which are presented in Table 1. Each rule consists of an IF component, a logical connection and a THEN component. The IF conditions are built using predicates, and a logical connection is used to connect antecedent and consequent parts, whereas the THEN statement gives a degree of membership function that befits the fuzzy variables involved. The demonstration of fuzzy logic inference is easier through example; thus one rule is used to show how the inference engine works and the outputs of each rule are combined for generating the fuzzy decision [20]. Consider a rule If DegreeofDirectness is MidDirected and RDistance is Intermediate then the FuzzyCost is High as an example of calculating the output of the specified rule. In our fuzzy inference system, consider a case where DegreeofDirectness is 0.771 and RDistance is 0.479 the output is 0.157.

This value (0.157) represents the Fuzzy Cost of the specified neighbour node. The FuzzyCost which has this value is due to its being less directed toward destination. It means our fuzzy inference system uses a compromised decision based on routing metrics (Direction and Distance) to select the best preferable neighbour node. This output is obtained by using Mamdani's fuzzy inference method [20]. Furthermore, Figure 7 depicts the correlation behaviour between input and output variables. The trend shows that the value of FuzzyCost output increases when the value of RDistance is between 0.55 to 0.43 and DegreeofDirectness increases. This is because the higher DegreeofDirectness or intermediate values of RDistance leads to a higher probability of fuzzy neighbour node selection (dark blue part).

3.2.3. *Defuzzification.* Defuzzification refers to the way a crisp value is extracted from a fuzzy set as a representation value. In our fuzzy decision making system, we take the

TABLE 1. Knowledge structure based on fuzzy rules

	IF		THEN
Rule	RDistance	Degree.Directness	Fuzzy-Cost
1	Far	Less Directed	Low
2	Far	Mid Directed	Medium
3	Far	More Directed	High
4	Intermediate	Less Directed	Medium
5	Intermediate	Mid Directed	High
6	Intermediate	More Directed	V.High
7	Close	Less Directed	V.Low
8	Close	Mid Directed	Low
9	Close	More Directed	Medium

centroid of area strategy for defuzzification. This defuzzifier method is based on Equation (7), as follows:

$$A = \frac{\sum\limits_{AllRules} x_i \times \beta(x_i)}{\sum\limits_{AllRules} \beta(x_i)} \tag{7}$$

where A is used to specify the degree of decision making, x_i is the fuzzy variable and $\beta(x_i)$ is its membership function. Based on this defuzzification method, the output of the fuzzy cost function is changed to the crisp value.

As mentioned before, the SRR protocol could not handle disconnected vehicular scenarios. For instance, when a packet carrier enters a partitioned network, and there are no neighbour nodes to forward packets towards destination, it simply drops the packet. To give another opportunity to the packet carrier node, it can switch to queue up packets until it finds neighbour nodes. In the next section, we propose a mechanism to switch between SRR protocols and queue up modes.

3.3. **Tackling network dis-connectivity.** In this section, we try to answer the question: how do packet carrier nodes switch between a connected and unconnected network? In our protocol architecture, hello messages are used by all vehicles to exchange information about their topology. Thus, we use this information to provide switching awareness of the packet carrier node. This traffic information is used by packet carrier nodes to switch between vehicular scenarios. Therefore, the input is traffic density and the output

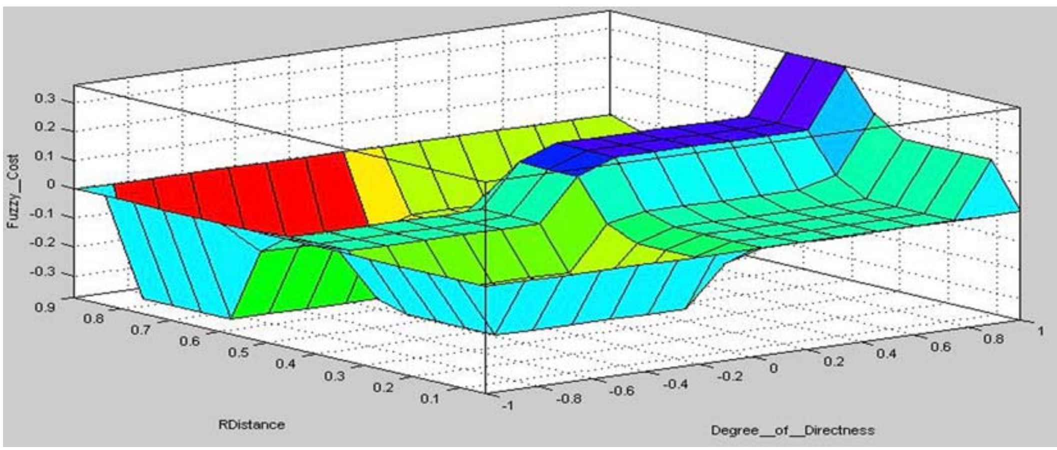


FIGURE 7. Correlation between input (DegreeofDirectness and RDistance) and output fuzzy variables

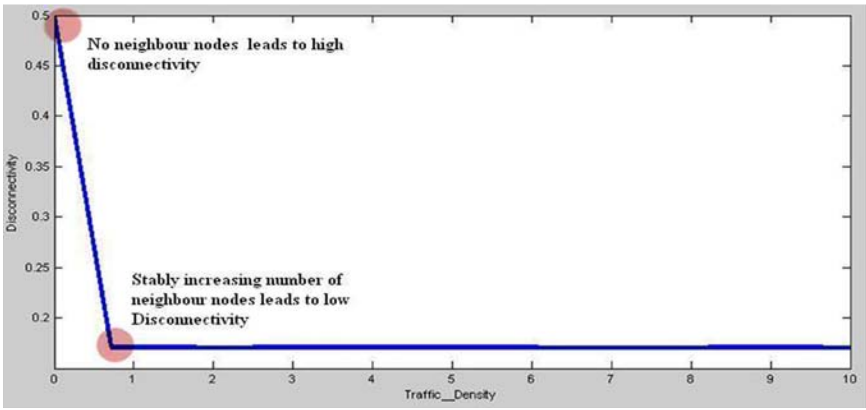


FIGURE 8. Relationship between traffic density within radio coverage of packet carrier node and its dis-connectivity

is the probability of dis-connectivity. Although the traffic density in VANET varies with space and time, we can find the traffic density of the packet carrier node by $\frac{\pi \times R^2}{\frac{(h \times w)}{n}}$[1], where R is the transmission range, $h \times w$ is the simulation area and n is the number of nodes in the simulation area. We now illustrate this equation by setting the values of $R = 250$, $n = 150$ (maximum number of nodes), $w = 1000$ and $h = 3000$, and the number of neighbouring packet carrier nodes is 10. Figure 8 illustrates the relationship between traffic density and dis-connectivity variables. The downward trend shows that higher densities lead to lower probabilities of dis-connectivity.

In addition, when a source/intermediate node has data packets but does not have a link to its neighbours, the data packets are cached in the buffer and the packet carrier node continuously checks for dis-connectivity [21]. After continuous checking, if the packet carrier node finds neighbour nodes, it utilizes the SRR protocol to forward data packets towards destination. In this way, we provide the data packets with another opportunity to salvage them from a partitioned network. Should the number of cached packets reach maximum queue threshold (which is defined in the simulator), the packet will be dropped by the packet carrier node. Moreover, it is worth mentioning that this method does not create any extra overhead on the network as this is a local decision making process.

4. **Analytical Model.** In Section 3, the algorithms of SRR and packet queue up modes have been proposed to route data packets in connected and dis-connected vehicular scenarios. This section proposes to analyze the switching mechanism between different modes of packet forwarding. Consider a vehicular scenario consisting of source, intermediate and destination nodes and the maximum radio coverage of vehicles is R_m (unit disc transmission range). The average number of neighbour nodes within the radio range (R_m) of a packet carrier node is given by Equation (8) [22]:

$$n_a = \frac{\pi \times R_m^2}{\frac{(h \times w)}{n_{si}}} \tag{8}$$

After that, we compute the transition probabilities between the modes of packet forwarding. The probability of cooperative awareness between a packet carrier node and its neighbour nodes is p. This probability p depends on the frequency of beacon transmission between neighbour nodes. When the n_a is known, the probability that a packet carrier

[1]We used this equation to clarify the theoretical computation of the traffic density, but in the simulation each vehicle computes the traffic density based on its neighbour table.

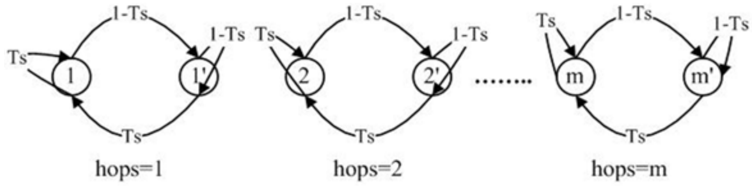


FIGURE 9. Discrete time Markov chain representing the state of packet carrier node

node communicating with the neighbour nodes within its radio range is given by:

$$P_f = 1 - (1 - p)^{n_a - 1} \tag{9}$$

When a node has been selected as a next packet forwarder, it has a T_s probability to remain in the SRR mode of packet forwarding. Then it successfully delivers data packets if at least one single node among n_a nodes exist in its radio communication range. Thus, the formula of T_s for m hops is given by:

$$T_s = \sum_{a=1}^{m} \binom{n_a - 1}{1} \times P_f \times (1 - P_f)^{n_a - 1} \tag{10}$$

It is noteworthy that we have proven the numeric value of T_s is between 0 and 1. Furthermore, the probability that the packet carrier node switches to the queue up mode is $1 - T_s$ and is determined by:

$$1 - T_s = 1 - \sum_{a=1}^{m} \binom{n_a - 1}{1} \times P_f \times (1 - P_f)^{n_a - 1} \tag{11}$$

Figure 9 illustrates the operation of the analytical model in terms of switching probabilities. When a node has been selected as a next forwarder, it has two choices. If it has at least one neighbour node within its radio coverage, it will remain in SRR mode with T_s probabilities. Otherwise, it will switch to packet queuing mode. Thus, through this model the packet carrier node is able to predict the probability that it will switch to queue up mode or remain in SRR packet forwarding mode or vice versa.

5. Performance Evaluation.

5.1. Simulation setup.
In this section, we present the simulation setup to validate and evaluate the proposed protocol. We have simulated the SRR protocol and the caching mode of data packets with the scalable and reconfigurable JiST/SWANS. To simulate the designed fuzzy logic, we have modified the implemented fuzzy inference system in [23], then integrated it with JiST/SWANs. Also, these simulations were executed on a Pentium(R) Dual-Core CPU 2.70 GHz and 2 Gb personal computer with installed Java $j2sdk1.6.0_18$. All simulation parameters are illustrated as follows:

- Physical Layer: In order to characterize the channel as lossy channel, we use log-normal shadow fading. Shadowing effect states that received signal power fluctuates in the presence of an object which obstructs the propagation path between transmitter and receiver. The received power fluctuates with "log-normal" distribution about the mean distance-dependent value [24]. The shadowing model is given by:

$$PL(d)[dB] = PL(d_0) + 10 \times n \times \log \frac{d}{d_0} + X_\sigma \tag{12}$$

where $PL(d)$ is the path loss at distance d between transmitter and receiver, $PL(d_0)$ is the average path loss at a reference distance of (d_0), n is the path loss exponent and

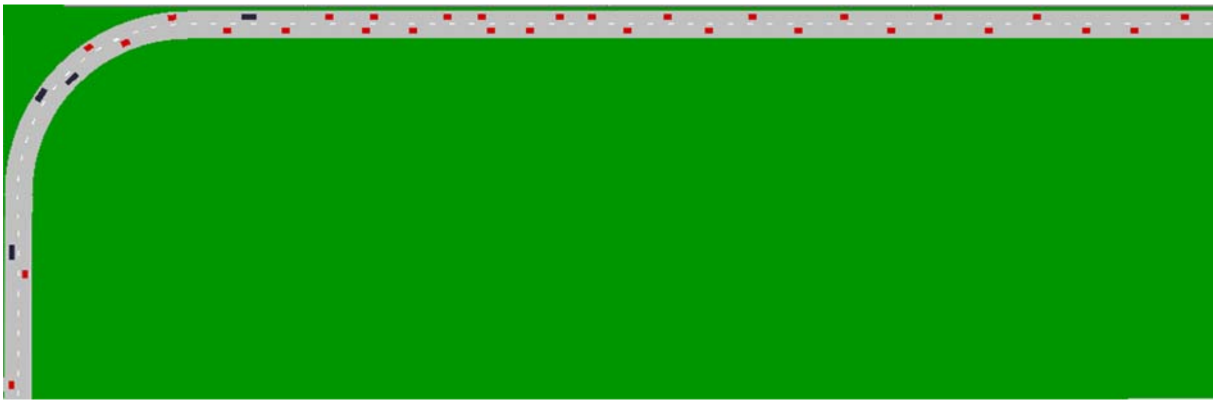


Figure 10. Realistic highway vehicular scenario

X_σ is a zero mean Gaussian distributed random variable with standard deviation σ. The values of path loss exponent $n = 2.8$ and reference distance $d_0 = 0.4$ are used for the shadowing propagation model. To evaluate the proposed protocol with different channel conditions, we vary the degree of standard deviation σ. Furthermore, all vehicles are communicating with default radio coverage of 200 meters.

- Mobility Model: To model a realistic highway vehicular scenario, we have used the mobility model in Application aware SWANS with Highway (ASH) [25] which is plugged to JiST/SWANs. This mobility model adds the functionality of Intelligent Driver Model (IDM) [26] and Minimizing Overall Braking decelerations Induced by Lane changes (MOBIL) [27]. Moreover, we set the maximum speed of the vehicles at 25 m/s.
- Media Access Control (MAC) and Network Layer: The IEEE Standard 802.11b distributed coordination function (DCF) has been used to simulate the MAC layer of the protocol stack. The channel bandwidth used in our simulation is 2 Mbps. To cache packets when they reach network dis-connectivity, we used a send First In First Out (FIFO) queue in the network layer to contain a maximum of 25 packets. On the other hand, in normal connected mode, we used SRR protocol to forward packets towards the destination. Further, in our simulation, the process of packet forwarding continues until the packet reaches destination or passes over 10 hops (TTL = 10 hops). We empirically set the value of TTL in the simulation. The simulator uses a buffer blocking function to control packet transmission or blocking; thus we used this function to cache packets once there is no neighbour node within the radio coverage.
- Traffic Model and Vehicular Scenario: The traffic source of the simulation is Constant Bit Rate (CBR). The frequency of packet generation rate is adjusted from a minimum value of (16 kbps) to a maximum value of (72 kbps). The number of source nodes is also varied from (5) to (15) and traffic density varies from 30 to 250 nodes over the total simulation area. During the simulation, the transmitted packet size is fixed at 1000 bytes. The simulation area is also fixed at 4000×500 meter, which is demonstrated in Figure 10.
- Simulation Time: The total simulation time is 160 seconds. We set the settling time at 30 seconds from the beginning of the simulation to remove the effect of transient behaviour on the results. The total simulation time also included 30 seconds of stop sending packets from the end of the simulation. It is worth mentioning that, each point in the performance figures exemplifies the average of 10 simulation runs.

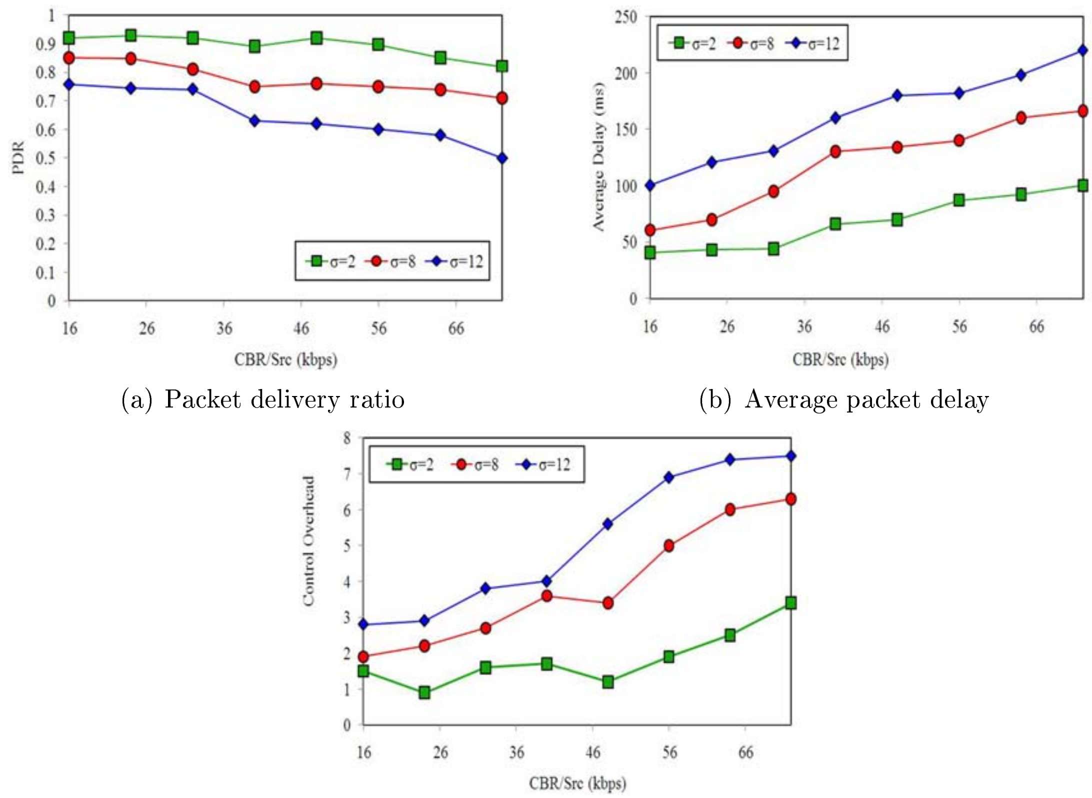
- Performance Metrics: The following metrics are considered in our performance evaluation: Packet Delivery Ratio (PDR) measures the fraction of data packets that are successfully received by the destination to those generated by traffic source; End-to-End delay is the total time required by all the packets from the source to the destination. The packet delay obtained in the simulation is the sum of sending buffer, medium access (packets delay due to interface queue), re-transmission and propagation delay; control packet overhead measures the number of control packets sent per number of data packets generated by a source. In SRR, the control packets are Clear To Send (CTS), Request To Send (RTS), ACKnowledgement (ACK) and Hello (H). Then we can find the Control Overhead (CO) as follows:

$$CO = \frac{Num(CTS + RTS + ACK + H)}{Num(DataPackets)} \tag{13}$$

5.2. **Simulation results.** As mentioned earlier, we evaluate our protocol based on various parameters. By varying the simulation parameters, we studied different experiments such as impact of lossy wireless channel between vehicles (σ), impact of vehicular traffic density, impact of vehicle speed and impact of number of source nodes. We also performed a comparative study between our protocol and standard protocols for geographical and topology based routing.

5.2.1. *Impact of channel shadowing.* In this experiment, the number of source nodes is 5, the total number of nodes in the simulation area is 150 (the network is connected) and the node speed is 25 meter/second. Figures 11(a), 11(b) and 11(c) demonstrate the effect of varying link error rates of wireless channels and CBR traffic per source on the PDR, average packet delay and control overhead respectively. As the value of standard deviation and source packet traffic increases, the PDR decreases accordingly. For instance, when the CBR value increases to 72 kbps, the PDR value of σ = 2, 8 and 12 are 82 %, 70.11 % and 51.01 % respectively. There are a number of reasons for this. First, high channel error leads to high packet losses due to the increased error rate of the wireless link between the packet carrier node and its neighbours (This packet loss occurs once retransmissions exceed the specified threshold, after which the transmission is assumed to be unsuccessful). Secondly, increasing the frequency of packet rate generation causes elevation of traffic load on the network, yielding higher packet contention at the MAC layer. In Figure 11(b), the trend of average packet delay increases as the channel error and data traffic rates increase. Initially, at scarce packet generation rates, the average packet delays are 40.57 ms, 60.534 ms and 100 ms when σ is 2, 8 and 12 respectively. After the packet generation rate reaches about 32 kbps, we observe upward transition of the packet delay to 160 ms when σ is 12 and then consistently reaches 220 ms at CBR = 72 kbps. We believe that this is because the network reaches its peak saturation throughput (which is the maximum limit of capacity that the network can carry in stable condition) at 32 kbps. Afterwards, packet loss occurs due to higher network load, combined with the fact that the larger the degree of standard deviation, the higher the degree of wireless channel loss. MAC layer tries to compensate for these packet losses at the cost of average packet delay. Although our SRR protocol selects a mid-distance neighbour node as a next relay node, its performance degrades with increasing degrees of wireless channel error. However, our SRR protocol performs better in comparison with other state of the art protocols (see Subsection 5.2.5).

Similarly in Figure 11(c), the SRR protocol with larger σ (12) suffers higher control overhead compared with the one with lower σ (2). Recall that the control overhead is measured as the number of control packets sent per number of data packets. When channel



(a) Packet delivery ratio (b) Average packet delay

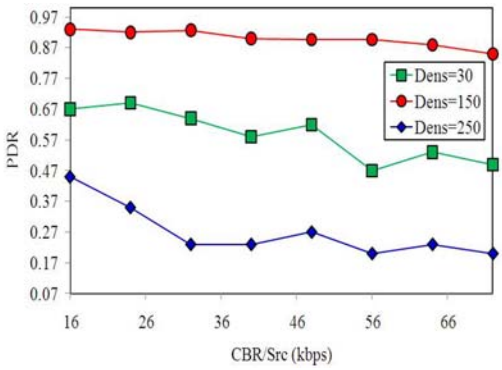
(c) Control overhead

FIGURE 11. Packet delivery ratio, average packet delay and control overhead versus packet sending rate under different degree of standard deviation σ

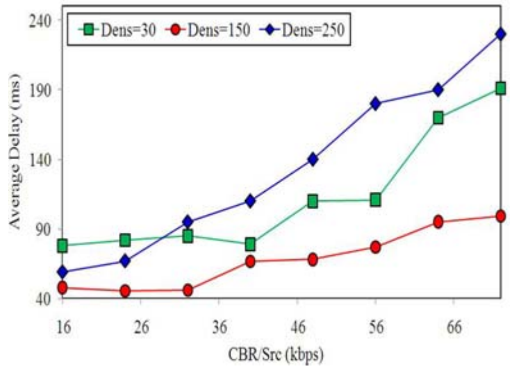
error and CBR per source increase, the data packet and control packet loss (RTS, CTS, ACK and Hello) also increase. The MAC layer tries to perform redundant retransmissions to compensate for these packet losses. With these packet retransmissions, the network is susceptible to higher control overhead. The experiment shows that increasing the degree of wireless channel error causes performance degradation of the routing protocol. In other words, the impact of increasing degrees of channel error and packet generation rates (beyond a value) severely degrades network performance.

5.2.2. *Impact of vehicular traffic density.* Our second experiment has been conducted to show the effect of traffic density variation for different values of CBR rate on SRR protocol. In this experiment, we set the node speed at 25 meter/second, the number of source nodes at 5, the degree of channel error at 2 and radio communication range at 200.

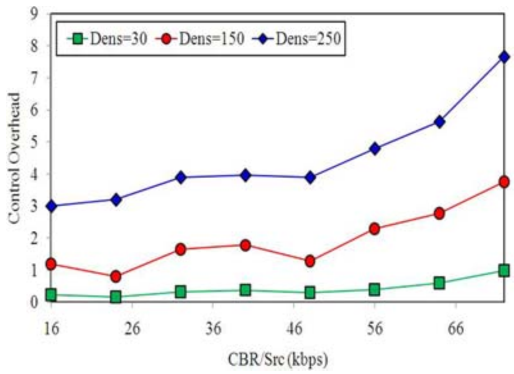
In Figure 12(a), the variation of PDR is plotted with respect to packet generation rate for different node densities (30, 150, 250). When the inter-packet arrival time is large, the packet delivery ratio degrades for 30, 150 and 250 densities. But, this descending of PDR is different for each density. For sparse/disconnected vehicular scenario (30 nodes), SRR trend starts at about 67.8 % then fluctuates gradually until it reaches 49.3 % at 72 kbps (18.5 % PDR degradation). The reason is that when vehicles are sparsely distributed, the nodes are likely to be far from each other and this causes route disconnection. For packet salvaging in a partitioned network, the packet carrier vehicle switches from SRR mode to queue up mode. Moreover, in VANET, carrying packets during route disconnection and forwarding them when neighbour nodes are present depends upon the mobility of



(a) Packet delivery ratio



(b) Average packet delay



(c) Control overhead

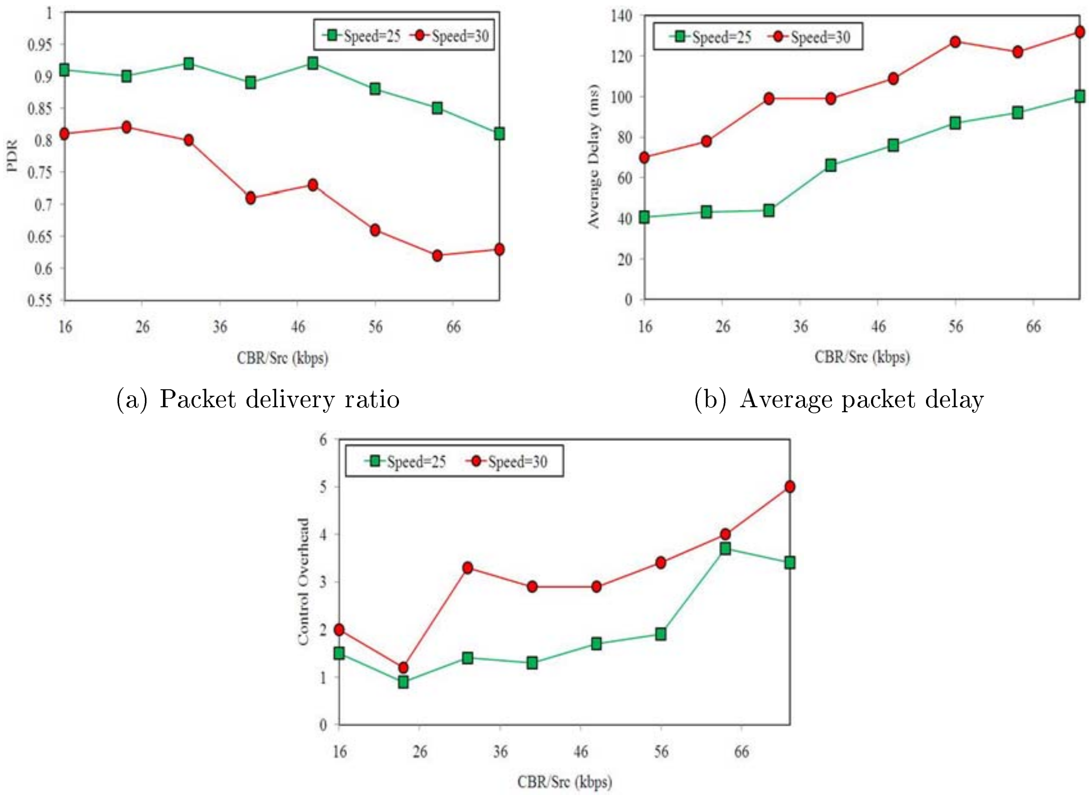
FIGURE 12. Effect of varying packet sending rate for different vehicular traffic density on packet delivery ratio, average packet delay and control overhead

nodes and their instantaneous placement. On the other hand, for congested vehicular scenario (250 nodes), the PDR trend drops acutely until it reaches about 20.3 %. This is no surprise, since the number of nodes increases to 250 in the 4000 $\times$ 500 simulation area. This leads to traffic congestion and hence the large drop in delivery ratio. In this experiment, we have shown the effect of node density on the performance of the proposed protocol and that it could tackle the dis-connectivity issue in sparse vehicular networks (maintain PDR in acceptable range). However, the improvement of packet delivery ratio is at the expense of higher packet delay due to the extra delay of carrying (queue up) packets (Figure 12(b)). This increase in packet delay can also be attributed to the fact that our protocol intelligently switches between SRR and the queue up mode. We observe that this is happening in Figure 14, i.e., the trend of average delay starts from 78 ms at 16 kbps, reaches about 95 ms at 31 kbps, and increases to about 211 ms at 72 kbps. However, due to rapid arrivals and departures of high mobile vehicular networks, we expect our combined geographical routing and caching mechanism to result in improved performance. Also, to show the behaviour trend of the network performance, we intentionally (250 nodes is on the simulation area 4000 $\times$ 500) experimented with a vehicular scenario with 250 nodes. As expected, due to network congestion, the average delay consistently increases.

Figure 12(c) shows the variation in control packet overhead with respect to frequency of packet generation for different densities. The trend of control packet overhead in the vehicular scenario with 30 nodes always lags behind the trend with 150 nodes and 250 nodes. This shows that our SRR protocol maintains neighbour nodes by broadcasting hello messages periodically, leading to higher overhead with greater number of nodes in the simulation area.

5.2.3. *Impact of vehicle speed.* This experiment is set with a total of 150 nodes on the simulation area, σ on 2 and transmission range of 200 meters. To show the effect of vehicle speed on the network performance metrics, we varied the frequency of packet generation rates for different vehicular speeds (25 and 30 m/s).

The effect of speed on packet delivery ratio is presented in Figure 13(a). We can see that when vehicles travel at higher speed (30 m/s), our protocol suffers a decline in successful packet delivery. In our simulation, the average loss suffered by the packet delivery ratio, as vehicles travel at different speeds, is 16 %. The reason is that when vehicles travel at higher speeds, the update of the neighbour information becomes inaccurate (vehicles are travelling with less cooperative awareness), resulting in the miss of the decided next forwarder and hence higher average packet latency (Figure 13(b)). We can note the average packet delay is elevated by 35.94 ms as the speed increases from 25 m/s to 30 m/s. As we mentioned before, control overhead is defined as the number of control packets sent per number of data packets generated by a source. As the speed of vehicles increases, the control overhead also increases. This is not just because of the hello packets, but also due to increased numbers of RTS, CTS and ACK packets. This observation can also be attributed to the fact that when a source decides on a preferred packet forwarder, it first starts to send RTS packets to the forwarder. The selected packet forwarder responds by CTS, and afterwards the source starts to send data packets. If the source does not receive the CTS packet in a specified time interval (e.g., due to higher travelling speed of



(a) Packet delivery ratio

(b) Average packet delay

(c) Control overhead

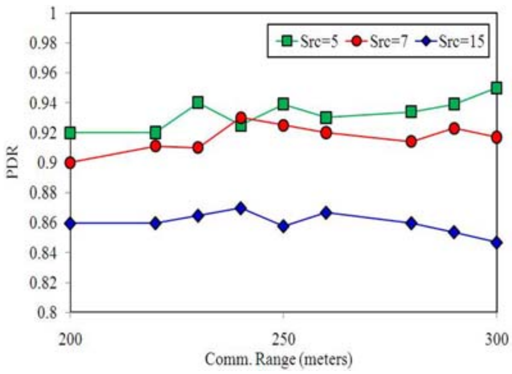
FIGURE 13. Effect of varying packet sending rate for different vehicle speed on packet delivery ratio, average packet delay and control overhead

vehicles), it retransmits the RTS and waits a bit longer (Figure 13(c)). Therefore, based on this experiment, it is fair to mention that our protocol is counter-productive as the speed of vehicles increases.

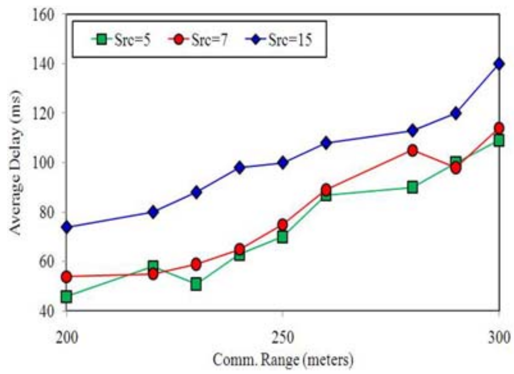
5.2.4. *Impact of number of source nodes.* To investigate the effect of source nodes and transmission range on the performance of SRR protocol, in this experiment we set the number of nodes at 150 (connected network), σ at 2 and CBR at 34 kbps whereas we varied the radio communication range for different numbers of sources (5, 7 and 15).

Figure 14(a) shows the PDR of a different number of sources (5, 7, 15) with respect to radio communication range. An apparent observation shows that while the number of source nodes is 5 and 7, the PDR increases consistently with increased radio range. More precisely, the PDR reaches optimal value as the radio range trend is between 230 to 250 meters. Also, the PDR optimal gain is noticed at 225 meters as the number of source nodes reaches 15. Further, notice that as the number of sources increases beyond the capacity of the network, the SRR packet delivery ratio degrades. We observe that precisely this is occurring, as the number of source nodes increased to 15 (see the value of 15 Src node at 258 meter). The trend of PDR descending at 258 meter of Src = 15 is sub-acute, which means that increasing the transmission power beyond a preferable value leads to sharp performance degradation. The reasoning is that when the number of sources is increased (beyond a limit), the load on the network is increased.

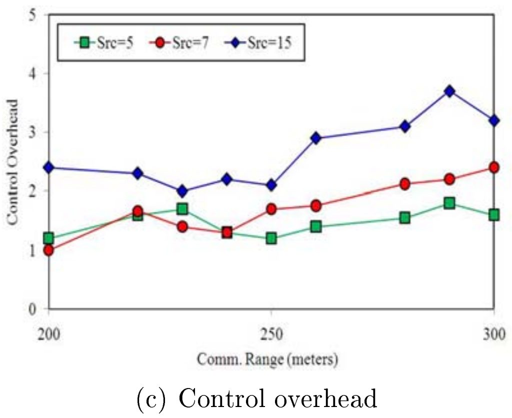
Considering the average delay metric, and although increasing radio range leads to routing packets with a fewer number of hops towards destination, the average packet delay of SRR protocol increases. By looking at Figure 14(b), where the packet delay is



(a) Packet delivery ratio



(b) Average packet delay



(c) Control overhead

FIGURE 14. Effect of varying packet sending rate for different number of sources on packet delivery ratio, average packet delay and control overhead

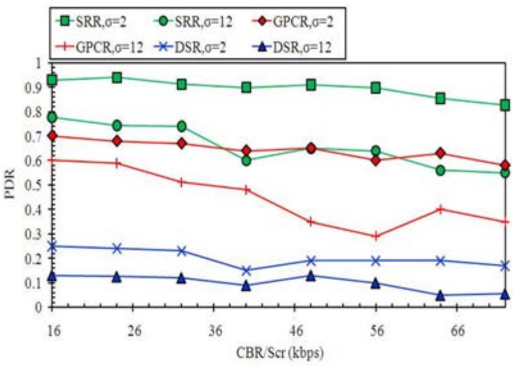
plotted versus radio range for a different number of sources, we note that precisely this is happening. We coin the reasons why the packet delay increases when radio range increases for Src is 5, 7 and 15. First, as the radio range increases, the number of nodes per radio range increases, which yields a higher level of contention, leads to higher delay. Second, we believe our SRR protocol incurs additional delays. The reasons include reactive neighbour node scoring, the decision to select a preferred neighbour node, and mid distance node selection (when the degree of standard deviation is 2).

Next, in Figure 14(c), we present the control overhead variation with respect to radio range for different numbers of sources. As can be seen, with a fewer number of source nodes (5 and 7), we note an obtuse ascending of the control overhead trend. This result is partly due to neighbourhood maintenance of the SRR protocol. On the other hand, when the number of sources is increased to 15, the trend of control overhead rises acutely at about 256 meters of radio range. The reason is that when we increase the number of source nodes on the network, the network load is increased too, combined with the fact that increasing radio range leads to more contention at the MAC layer. It is noteworthy that we also ran the simulator by varying the frequency of packet generation for different numbers of sources. We noted that the average PDR decreases, whereas the average packet delay and control overhead increases.

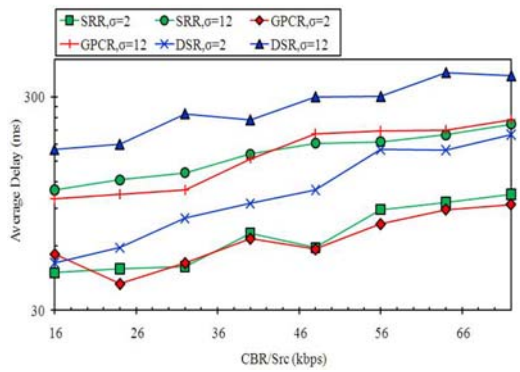
In this experiment, we have shown that setting the optimal radio communication range and the number of source vehicles is crucial and these factors have an impact on overall network performance as well as on the routing protocol. Further, the optimal radio range that we observed is between 230-250 meters.

5.2.5. *Comparison study.* In this section, we compare the performance of the SRR protocol with the state of the art geographic routing (GPCR) and topology based (DSR) routing protocols. Since the java source code of GPCR is not publically available, we implemented it for comparison purposes. We now briefly review the basic operation of these protocols: GPCR is a geographical routing protocol that forwards packets to a node which has the shortest distance towards destination (greedy mode of forwarding). In the perimeter mode, a node forwards packets to the next neighbour by applying right hand rule; DSR is a topology based source routing protocol. That is, the source has information of the entire hop-by-hop route to the specified destination. Thus the source uses the cached routes then adds it to the packet header towards destination. Moreover, for this comparison study, we set the radio range at 250 meters, and the number of sources at 5.

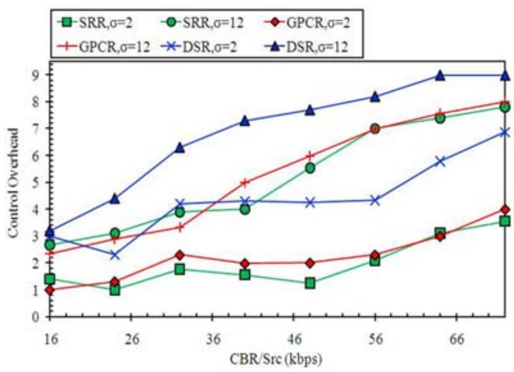
In order to investigate the impact of lossy wireless channels on the performance of different protocols, we varied the inter-packet arrival time for different degrees of standard deviation. Figure 15(a) outlines the packet delivery ratio under different CBR, with the standard deviation taken as 2 and 12. As depicted in Figure 15(a), the packet delivery ratio for all protocols decreases as the frequency of packet generation rates increase for different degrees of standard deviations. However, DSR suffers to a great extent from packet delivery degradation. The performance smash of DSR is due to the rapid movement of vehicles on the highway as well the fact that it relies on topology based routing; thus, constructed routes toward destinations break down frequently. On the other hand, we observe that the GPCR protocol always lags behind the SRR protocol. This can be attributed to the fact that GPCR, in greedy mode, selects the next packet forwarder which has the shortest distance to the destination, and since the wireless channel is lossy, it leads to signal attenuation and hence packet losses. In addition, GPCR does not take the destination direction into consideration, with the result that it may select a neighbour node whose direction is opposite to the destination node, potentially leading to packet loss due to faster link breakage. Therefore, our SRR protocol, which selects a packet forwarder node based on the distance between source and next forwarder, as well as the relative direction of the packet forwarder and the destination, is far superior in forwarding data packets successfully. This can be seen at $\sigma = 12$ the average PDR is 65.75 % for SRR protocol, but for GPCR is about 44.63 %. On the contrary, as demonstrated in Figure 15(b), at $\sigma = 2$, GPCR performs better compared with SRR and DSR. This is because SRR forwards packets in baby steps toward the destination. Furthermore, in general, forwarding packets over a higher number of hops leads to higher delay. However, at $\sigma = 12$ the results do not significantly follow this hypothesis. The reason is that when the degree of wireless error increases to its peak value, the selection of farthest neighbour node leads to higher packet loss, which yields higher packet re-transmission by the MAC layer, resulting in higher packet delay. Notice that this happens exactly at $\sigma = 12$ and $CBR = 45$ kbps, where SRR protocol falls behind the GPCR protocol. Now consider the control overhead metric: as the frequency of packet generation and wireless channels increase, the control overhead of all protocols also increase. Although SRR and GPCR have the same formula of control overhead (both of them maintain neighbour nodes), at lossy wireless channel, our protocol performs better in terms of average control overhead (Figure 15(c)).



(a) Packet delivery ratio



(b) Average packet delay



(c) Control overhead

FIGURE 15. Packet delivery ratio, average packet delay and control overhead for SRR, GPCR and DSR in a network with 5 sources, 150 node and variable frequency of packet generation rate with different lossy channel

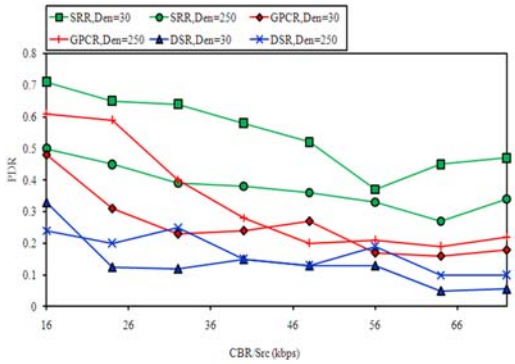
Next, we examine the performance of the protocols in extreme vehicular scenarios, the sparse scenario with a low number of vehicles (30) and the congested scenario with a high number of vehicles (250), as shown in Figure 16(a). In the sparse scenario, SRR protocol gives a better packet delivery ratio than GPCR and DSR protocols; the average improvement is about 29.38 % and 37.88 % compared with GPCR and DSR respectively. The performance hit of DSR is mainly due to frequent link breakage which causes invalid routes. Besides, single link breakage close to the source node may lead to invalid routes. Moreover, since in disconnected (partially connected) networks, GPCR simply drops the enqueued packets, our SRR has far higher PDR than GPCR. In dense traffic conditions, the improvement is about 3.98 % and 16.8 % compared with GPCR and DSR respectively. We believe that the performance hit of GPCR is mainly when GPCR selects the next neighbour node which is the closest to the destination, which may cause the miss of a selected neighbour node due to faster exit from the radio communication range. This also contributes to higher packet delivery delay (Figure 16(b)). Figure 16(b) illustrates the effect of packet generation rate on SRR, GPCR and DSR when traffic density is taken as 30 and 250 vehicles. In sparse vehicular scenarios, surprisingly, the packet delay trend of GPCR protocol can excel the SRR protocol. We reason that GPCR has lower delay (at the expense of delivery ratio) than SRR protocol. First, when the network is disconnected, GPCR simply drops packets, which does not contribute to packet delay. Second, SRR protocol queues up packets until it finds neighbour nodes in its coverage area, and then starts forwarding the packets using SRR protocol. Third, GPCR rarely switches to the perimeter mode in highway traffic scenarios. Moreover, Figure 16(c) shows the impact of extreme vehicular scenarios on the routing protocols control overhead. It can be seen that all protocols suffer increased overhead as traffic density increases to 250. But, on average, SRR performs better than the state of the art protocols. As seen, although GPCR and SRR follow the same procedure for neighbourhood maintenance, SRR offers marginally better performance. This is no surprise, since our strategy is based on multi metric packet forwarding which implicitly reduces control overhead of the MAC layer.

5.3. **Discussions.** This section focuses on a general comparison of SRR with state of the art routing protocols such as GPCR and DSR in terms of their packet delivery ratio, average packet delay and control overhead.

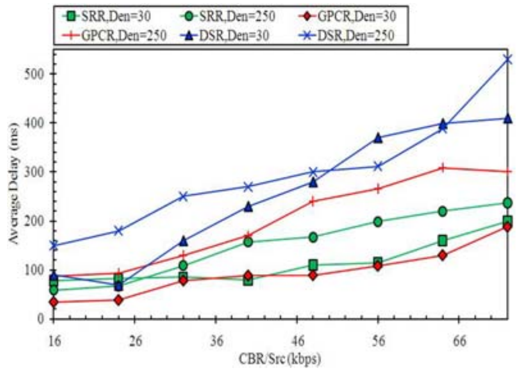
First, in Table 2, we summarize the average PDR, packet delay and protocol control overhead for SRR, GPCR and DSR. In terms of PDR, the performance of all protocols decreases as the degree of channel error increases. But, in terms of packet delivery ratio under high and low lossy channel, the DSR and GPCR always lag behind the SRR protocol. However, this is at the cost of packet delay. As mentioned earlier, the reason GPCR performs poorly is that, when GPCR selects the next neighbour node which is the farthest distance from the source node, it may miss the selected neighbour node due to faster departure from radio communication range. However, SRR makes a next hop decision based on relative direction and mid-distance from the source node. Next, in Table 3, we distill the impact of vehicular traffic density on the performance metrics for SRR, GPCR and DSR. In terms of packet delivery ratio, SRR performs better than GPCR and DSR. But, in sparse traffic conditions, our protocol offers higher delay than GPCR as delay is not counted for the packets which are dropped.

Table 2. Average packet delivery ratio, delay and control overhead with different degree of standard deviation

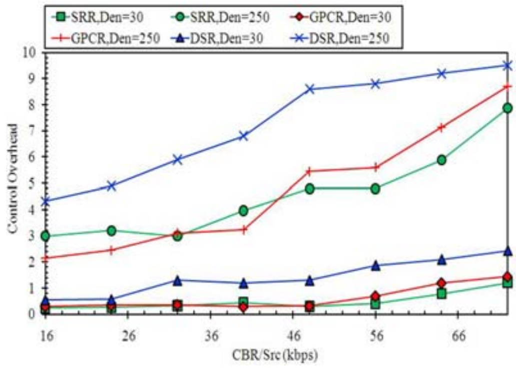
	PDR, $\sigma = 2$	PDR, $\sigma = 12$	$Delay$, $\sigma = 2$	$Delay$, $\sigma = 12$	CO, $\sigma = 2$,	CO, $\sigma = 12$
SRR	89.62 %	65.75 %	69.75	167.68	1.96	5.17
$GPCR$	64.38 %	44.63 %	65.87	156.87	2.23	5.25
DSR	20.12 %	10.01 %	116.75	275	4.39	6.88



(a) Packet delivery ratio



(b) Average packet delay



(c) Control overhead

FIGURE 16. Packet delivery ratio, average packet delay and control overhead in extreme vehicular scenarios with variable inter-packet arrival time. The degree of standard deviation is 2.

TABLE 3. Average packet delivery ratio, delay and control overhead in extreme vehicular scenarios

	PDR, $Node = 30$	PDR, $Node = 250$	De, $Node = 30$	De, $Node = 250$	CO, $Node = 30$	CO, $Node = 250$
SRR	54.82 %	37.73 %	113.62	151.87	0.49	4.56
$GPCR$	25.48 %	33.75 %	72.37	199.625	0.623	4.72
DSR	13.63 %	11.69 %	172.47	297.62	1.41	7.25

The presented results obtained from comprehensive performance evaluation indicate that the proposed SRR solution is suitable to forward packets in vehicular networks for a wide range of interesting services that require multi-hop communication. For instance, in distributed infotainment-related applications, vehicles can leverage the proposed routing protocol to send instant messages, files, geographic service advertisements or more general position-based publish-and-subscribe services along the highway vehicular environments.

Further, since the average time required by the fuzzy inference systems is 5.45 ms (this time tightly depends upon computer performance), its low overhead makes the proposed SRR protocol in vehicular networks feasible. Moreover, advances in chip manufacturing technology allow the practicality of embedding a fuzzy decision making system in hardware chips. Therefore, it is feasible that our fuzzy logic based SRR protocol can guarantee low complexity implementation from both software and hardware perspectives.

6. **Conclusions.** In this article, we have proposed a fuzzy logic based Stability and Reliability aware routing protocol called SRR to route data packets over more directed and reliable paths toward destination. As discussed in detail in this article, the proposed protocol can reactively route data packets towards the destination by giving the highest score to a neighbour node which is directed more towards the destination and is mid-distant from the current packet carrier node. In disconnected traffic conditions, the vehicles retain packets rather than simply drop them. Furthermore, we proposed an analytical model to compute the switching probability between extreme vehicular traffic conditions. Our protocol's intelligent adaptive feature of switching between SRR and queuing mode makes it suitable for rapid arrival and departure characteristics in VANET (sparse and dense scenarios). Extensive and fair simulation results show that, compared with the representatives of geographical (GPCR) and topology (DSR) routing protocols, our protocol performs the best in terms of average packet delivery ratio and control overhead. In terms of average packet delay, in dense traffic conditions, our protocol performs best. We are currently working on developing SRR so that it will be suitable for routing between intersections in urban vehicular scenarios. We can then integrate it with an intelligent mechanism for packet forwarding decisions at the intersections. Furthermore, it is important that error correcting codes such as forward error correction or random linear network coding are combined with routing protocols so as to increase the reliability of the data packet transmission.

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