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A Hybrid Relay Node Selection Scheme for Message Dissemination in VANETs

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Abstract

Over the past few years, there has been growing research interests on vehicular ad hoc networks (VANETs) due to their ease of deployment and the potential support for wide range of applications that can greatly enhance our everyday driving experience. Multi-hop messaging is expected to be the primary mode of communication among vehicles in numerous VANET-based applications including road safety, traffic management and infotainment services. Proper selection of the next-hop relay nodes is an essential part in the design of multi-hop message dissemination schemes in VANETs, which highly governs the reception of the broadcasted messages, especially when evaluated over large coverage distances and high node density networks. Existing message dissemination schemes adopt only a single relay nodes selection criterion for choosing nodes in the group of next-hop relays. However, potential of the selected relay nodes can be restricted due to exploiting only a single selection criterion, hence limiting the performance outcomes. This research proposes a new class of hybrid relay nodes selection scheme that attempts to exploit the best features of existing message dissemination protocols, in terms of message reachability, communication delay and bandwidth utilization, while avoiding their shortcomings. The new hybrid scheme takes into account the spatial distribution of the next-hop relay nodes with reference to the current sending node. To the best of our knowledge, the present study is the first in literature to propose such a hybrid scheme that attempts to improve performance of VANETs over varying node densities, traffic load conditions and mobility speed scenarios. Over the most stringent communication scenario considered in this work, our performance analysis indicates that the new hybrid scheme improves reachability by up to 10% compared to the most competitive conventional versions. This improvement is obtained while having a marginal performance fall in terms of the end-to-end communication delays and messages saved rebroadcast ratios.

Keywords: Hybrid, relay, VANETs.

1. Introduction

Enabling direct wireless communication among vehicles is a core component of the envisioned Intelligent Transportation Systems (ITS) [1-3]. The directly connected vehicles are commonly referred to as Vehicular Ad Hoc NETworks (VANETs) [4-6]. The endorsement of information and communication technologies in vehicles can enhance drivers' awareness of immediate and far distant traffic situations. Consequently, VANETs can lead towards more intelligent decisions to deal with the dynamic road-related events [1, 3]. VANETs can support a wide spectrum of applications including road safety services, traffic flow and congestion management [7, 8]. On top of that, it is envisaged that VANETs will become the de-facto enabling technology for communication among vehicles on the road [9].

Multi-hop messaging is expected to be the primary mode of communication in VANETs that can be utilized for diversified set of applications [1, 10]. In particular, a timely and successful reception of messages can be used for the reduction of high speed road accidents by providing early warning messages to nearby and far distant vehicles, hence increasing the reaction time to the advertised situations [11]. VANETs can facilitate small to large propagation areas for the broadcasted messages through multi-hop mode of communication, with coverage distances spanning from few hundred meters to several kilometers [12]. Proper selection of relay nodes is an essential part in the design of multi-hop message dissemination schemes, which highly governs the reception of the broadcasted messages, especially when propagated over large coverage distances and high node density networks [13-15]. A poor selection of the relay nodes can lead to the loss of messages, hence significantly limiting the reception of messages. The success and failure in relay nodes selection becomes even more critical when the broadcasted messages are critical-in-nature, such as accident advertising alert messages.

High reachability and low end-to-end delay are among the key requirements of any message dissemination scheme in VANETs [16, 17]. Furthermore, messaging schemes should ensure efficient utilization of the channel bandwidth, a resource that is often scarce. Several schemes have been proposed to achieve the above described goals, in which furthest distance (FD) based schemes are the most commonly adopted for obtaining low end-to-

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end communication delay [16, 17]. However, higher probability of messages loss is possible when selecting nodes falling furthest in distance as relay nodes [18-20], which is due to the adverse channel effects, hence resulting into degrading reachability performance. In contrast, link quality based message dissemination schemes have gained popularity as an alternative solution to FD schemes and has shown to obtain better performance levels in terms of reachability [20-24]. Though, several link quality based message dissemination schemes have been proposed in literature, our previously proposed Bi-Directional Stable Communication (BDSC) scheme has shown superior performance over its competitors in varying network conditions [21-23]. The BDSC scheme employs a *sender-oriented* relay nodes selection mechanism, where this mechanism is realized for its capability in improving bandwidth utilization by reducing rebroadcast redundancies [16, 25].

Existing message dissemination schemes designed using the *sender-oriented* mechanism adopt only a single criterion for selecting all the nodes in the group of next-hop relays [16, 19, 2[illegible]], which we will refer to in this work as “conventional” schemes. Both BDSC and FD adopt the design of the conventional scheme. Figure 1 presents an example of relay node selection in the conventional FD scheme in which IDs of the next-hop $C = 12$ relay nodes are selected using only a single criterion, which is in this case the FD. This selection process is further elaborated in Figure 2 in which the source node A selects only those $C = 12$ relay nodes that fall furthest in distance from its current position, represented by the nodes O, P, Q, R, S, T, U, V, W, X, Y, Z. In addition, Figure 2 portrays the spatial distribution of the selected relay nodes by source A in which only nodes falling furthest in distance are exploited while the nearer ones are neglected. However, it is possible that potentials of the nodes falling nearer to the source will be overlooked when exploiting only FD for selecting the relays.

The above described phenomenon is not limited to the conventional FD scheme but has also been observed with other conventional schemes that have been proposed for VANETs [21-23]. In general, the selected relay nodes usually fall in close proximity to each other while adopting the conventional schemes, hence restricting the spatial distribution, in the selected set of relay nodes, to a specific region. Consequently, somewhat similar performance outcomes are expected by the selected relays. This limitation can be mitigated if the full spectrum of the spatial distributions can be exploited systematically. In general, it has been observed in literature that conventional schemes exhibit promising performance in terms of saved rebroadcast but have several shortcomings in-terms of end-to-end delays and reachability, especially when evaluated over densely populated VANETs [21-23].

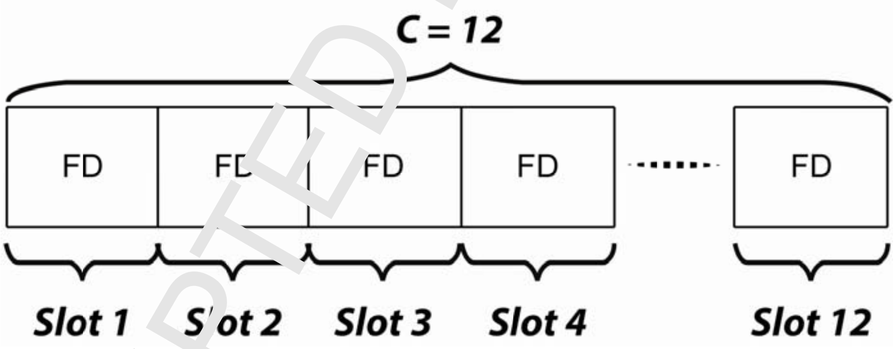


Figure 1: Relay nodes selection in the conventional FD scheme.

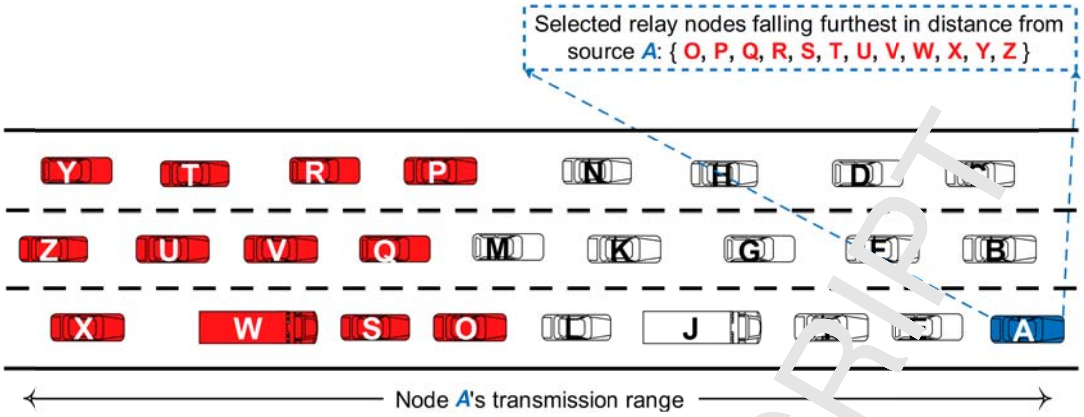


Figure 2: Spatial distribution of the selected $C = 12$ relay nodes when exploiting FD as the only criterion for the next-hop relay nodes selection over a platoon of vehicles.

In light of the above-described limitations, there is a need for combining multiple relay selection criteria for exploiting their best features in terms of reachability, end-to-end delay and saved rebroadcast, and while suppressing their shortcomings. So far, such a challenge has not been addressed in the literature yet. However, devising a message dissemination scheme that ensures good performance levels is a challenge given the inherent dynamically changing topology and traffic conditions in VANETs [26-29]. In an effort to fill this gap, this paper proposes a hybrid scheme in which a *sender-oriented* relay selection mechanism is adopted while the next-hop relay nodes are selected using multiple relay selection criteria. The proposed scheme attempts to select relay nodes while combining the selection criteria used in FD and BDSC schemes in particular ordered combinations. In this work, the combination focus have been placed over the FD and BDSC schemes, since FD has the potential to reduce end-to-end delays [16, 17] while BDSC has shown promising improvements in-terms of reachability over high node density networks [21-23]. Having said that, the hybrid scheme does not limit itself in employing FD and BDSC schemes only. In-fact, the combination of other message dissemination schemes can also be put into investigation while employing the suggested steps for devising a hybrid scheme. The hybrid scheme attempts to fulfill the requirements of a wide spectrum of applications spanning from road safety to infotainment services, with focus on improving message reachability in the presence of heavy communication over a dense network. The core contributions of this work are as summarized below:

- A hybrid scheme that attempts to exploiting the potentials of multiple relay selection criteria for choosing the group of next-hop relay nodes.
- The design principles adopted for devising the hybrid scheme.
- Structure of the two variants within the proposed hybrid scheme.
- Study the performance impact of varying node density, traffic load and mobility speed scenarios over the proposed hybrid scheme.

The rest of the paper is organized as follows. Section 2 discusses the related work with an emphasis on the most recent studies. Section 3 provides a brief discussion on the exploited BDSC schemes as a base component in the proposed hybrid scheme. Section 4 discusses the design principles followed for devising the hybrid scheme along with the ordered-combinations of the two proposed variants within the hybrid scheme. Section 5 presents the simulation environment, assumptions and the parameters of the selected mobility models. Section 6 discusses the attributes of the hybrid schemes w.r.t. the suggested design principles. Section 7 evaluates performance of the hybrid scheme and analyzes the obtained performance results. Finally, Section 8 provides a conclusion for this work along with future research directions.

2. Related Work

VANETs are self-organizing networks and facilitate communication among vehicles without the need for costly infrastructures [4-6]. In VANETs, vehicles function as *nodes* where each can play the role of a *host* as well as of a *router* [1, 2]. The amount of in-lab research and on-road tests related to VANETs have intensified over the past few years [1-3]. This has been fueled by the fact that VANETs can play a key role in improving road safety and traffic flow efficiency along with a variety of comfort and infotainment applications, where the reduction of road traffic accidents has been the mainstream research focus in VANETs [12, 17, 29-31]. In general, broadcasting is employed in VANETs for the dissemination of both single-hop *HELLO* packets and multi-hop application messages [32]. The information incorporated inside the periodically broadcasted *HELLO* packets is a valuable source for a given node to learn about its surrounding conditions, such as the neighboring nodes' mobility speed, travelling direction, positioning coordinates and relative distance [16]. On the other hand, the information within the application messages are utilized to further rebroadcast the received messages to upstream nodes, such as the dissemination of event-driven alert messages for advertising nearby road accidents.

The multi-hop message dissemination in VANETs is generally categorized as being either *localized* or *distributed* [33], based on their independency and dependency on the neighboring nodes information, respectively. The localized routing approach does not gather neighboring nodes information, where a node solely takes a routing decision based on the local information it holds or those which have been received with the message to rebroadcast [34]. Localized mechanisms have low overheads due to the absence of information exchange among neighboring nodes. However, this comes with the cost of being unaware of surrounding nodes situation that can act as a major setback for many VANETs based applications, especially for safety related messaging schemes. In contrast, a distributed routing requires frequent updates on the neighboring nodes, usually gathered through periodic *HELLO* packets [16, 17]. In a distributed routing approach, a node can be aware of various information about the surroundings at the cost of increased overheads in the exchanged control packets. However, several techniques have been proposed for suppressing the overhead causes by the periodic exchange of *HELLO* packets in distributed routing, such as using probabilistic broadcasts [34].

Selection process of the relay nodes is usually classified as being either *receiver-oriented* or *sender-oriented* [33]. In the receiver-oriented relay nodes selection, all nodes receiving the broadcast message contend for becoming the next-hop relay [17]. As a result, the relay is implicitly decided on the fly by the message receiving nodes. However, the receiver-oriented relay nodes selection leads towards redundant rebroadcasts of the message resulting in poor utilization of the available bandwidth. In the sender-oriented relay nodes selection, the source node takes the responsibility of explicitly selecting a group of nodes from which the nodes contend for becoming the next-hop relay [16, 19, 25, 35]. The motive behind employing a sender-oriented relay nodes selection is two-folds. The first is to explicitly regulate, at the sender side, the number of nodes that contend for forwarding the received messages. The second is to explicitly regulate the waiting time each node has to wait before accessing the channel for message rebroadcast. With assistance of this regulated rebroadcasting mechanism, a reduction in message rebroadcast redundancy is obtained, leading towards efficient utilization of the channel's bandwidth.

Opting towards a *sender-oriented* relay selection requires defining the relay cardinality at the sender side, where the maximum number of IDs that can be accommodated in this list of next-hop relays can be defined as the relay nodes cardinality C. Improper cardinality can lead to inefficient performance, where a small cardinality can result in loss of the disseminated message if all nominated nodes fail to rebroadcast while a large cardinality can increase the rebroadcast redundancy if the relaying node fails to notify the other contending relays [16, 25]. Most research on multi-hop messages dissemination in VANETs has mainly emphasized on the reduction of end-to-end delays over a platoon of vehicles [12, 16, 17, 19, 36]. Reduction of end-to-end delay is usually addressed by choosing relay nodes falling furthest in distance from the source, also defined in literature as greedy or progress distance based message dissemination scheme [16, 17, 36].

A message broadcasting scheme termed as privileged inter-vehicular communication architecture (PIVCA) was proposed in [17], and further utilized in [36] for the reduction of end-to-end delays. PIVCA proposes to estimate the forward and backward transmission ranges to the single-hop neighboring nodes with assistance of the information exchanged within the periodic *HELLO* packets. At the time of messages dissemination, a receiver-oriented relay selection mechanism is adopted where PIVCA utilizes the estimated transmission range for optimizing the relay nodes' waiting time before rebroadcasting the received messages. In [16], an asymmetric transmission ranges among single-hop neighboring nodes is considered, where intermediate nodes are used to convey *HELLO* packets between any pair of nodes of which one of the nodes is not able to hear the other directly. In the same work, a furthest-spanning relay selection scheme is introduced which is a variant of FD scheme. The furthest-spanning scheme selects the set of nodes which have the largest sum of distances from source and their transmission ranges. Relay nodes having larger furthest-spanning distance would have smaller rebroadcast waiting times, and hence higher chances of becoming relays.

A broadcasting protocol has been introduced in [19], referred to as the multiple candidate relays opportunistic broadcast (MCROB) protocol. The MCROB protocol, aims to reduce communication delay by adaptively assigning dynamic waiting time to the relays candidates before forwarding the received messages. An expected transmission speed (ETS) metric is proposed to evaluate the performance of broadcast transmission speed. Simulated performance evaluation shows that MCROB protocol increases the average transmission speed by approximately 40%. In addition, a retransmission mechanism is adopted to enhance messages reception reliability. Density-aware emergency message extension protocol (DEEP) was proposed in [12] for the dissemination of emergency messages in VANETs. In this work, alert messages dissemination over large coverage area was discussed, where the targeted area was divided into three segments and provided with different alert messages reception priorities. The protocol was designed with the aim that nodes in the nearest and the furthest segments should receive the alert messages reliably, whereas nodes in the middle segment should forward the alert messages as quickly as possible. Reliability is addressed by adaptively configuring the number of alert messages retransmission according to the surrounding nodes density over a given block size. The fast forwarding mechanism was achieved by providing smaller waiting time to nodes residing in segments that are further away from the source. The proposed solutions in [12, 16, 17, 19] utilizes the FD technique when selecting the next-hop relay nodes. With the limitations in the FD based schemes, described in Section 1, the methods in [12, 16, 17, 19] can result in heavy losses of the transmitted messages, especially over high node density VANET.

A link metric, termed as expected progress distance (EPD), has been introduced in [20] to assess the transmission link quality between nodes in a VANET. The EPD measures the packets transmission failure rate for both forward and reverse links. The forward link's error rate is reported by the neighboring nodes, whereas the reverse link's error rate is a measured quantity at the receiver. However, loss of the occasional packets that report the forward link's error rate could lead towards faulty estimations of link qualities, hence faulty selections of relay nodes. The computation of EPD metric is dependent on both forward and reverse link qualities, where poor reverse links' performance may overshadow the good performance of forward links, resulting in neglecting those potential forward links. In addition, piggybacking of the forwarding link quality while broadcasting the periodic *HELLO* packets is an additional overhead to bear. A path diversity mechanism has been proposed in [35] which selects two nodes at each message rebroadcast, one as a relay and the other as an auxiliary broadcast node. The relay node performs multiple functions by rebroadcasting the received messages, selecting the next relay and selecting an auxiliary node. The auxiliary node augments the relay nodes' broadcasts by only rebroadcasting the message without performing any relay nodes selection. High reachability of messages is possible while employing the path diversity mechanism in [35] but at the expense of additional channel bandwidth utilization due to the usage of two separate broadcast paths.

A selective forwarding scheme for multi-hop alert message dissemination in VANETs was proposed in [25], which efficiently utilizes the bandwidth by assigning a limited set of nodes as the contending relays. In this scheme, a *sender-oriented* relay nodes selection is adopted while assigning nodes having larger distance and lower velocity difference with the source a higher priority for becoming the next-hop relays. The *sender-oriented* relay selection concept proposed in [25] is adopted for the hybrid scheme proposed in this work, which plays a major role in improving the efficiency of bandwidth utilization, measured in-terms of saved rebroadcasts. A clustering and probabilistic broadcasting (CPB) is proposed in [27] to provide stable and reliable communication among nodes. Vehicles are group in form of clusters and data among vehicles is exchange through a cluster head, whereas cluster members use probabilistic forwarding to forward their data to the cluster head. The authors select cluster heads based on node's channel condition calculated by the adopted Nakagami channel model. However, the Nakagami channel model is term as not being an accurate model that could represent the channel conditions among the vehicles. Furthermore, the adopted probabilistic selection of forwarding nodes inevitably results into rebroadcast redundancies, hence degrading performance in-terms of bandwidth utilization which the authors have not evaluated in their work.

An Energy Efficient Routing Protocol for Vehicular Ad Hoc Networks, named as GreeAODV has been proposed in [37]. In communication between any two nodes in VANETs, GreeAODV aims to reactively select the most efficient routing path in-terms of energy consumption, by estimating the total power consumed between source and destination. Several distributed models have been devised to handle services management in vehicular networks, among them is a concept of Vehicular Trusted Third Party (VTTP) that is proposed in [38] which allows drivers to exploit the benefits of different services. Simulation results indicate significant reductions in services latency, which in-turn could greatly benefit in different VANETs-based applications, especially in safety services. Our previously proposed BDSC scheme introduced a forward link quality based relay nodes selection scheme which has shown improvements in-terms of messages reachability when compared to similar existing solutions, especially over highly dense networks [21-23]. The scheme also managed to maintain low end-to-end delays comparable to those obtained by the FD schemes. Different variants of the BDSC scheme have been suggested where it has been observed that one variant tends to outperform the other ones over certain network conditions while fails to do so over other conditions.

In addition to the above discussed different techniques adopted for devising message dissemination schemes in VANETs, deep learning models have shown strong potential in optimizing the relay nodes selection process [39]. Deep learning has drawn substantial attention due to its noticeable progress in several areas such as image classification and video game playing [40, 41]. In-fact, several deep learning frameworks have been developed in VANETs in relation to multi-hop messages dissemination [42]. These deep learning frameworks aim to learn the dynamics of the network followed by making decisions aiming towards network performance optimization along with improving road safety services such as the prediction of rear-end collision detection [42]. Further, the incorporation of random walk models have shown potential to optimize relay nodes selection in VANETs. Several graph-based algorithms have been proposed based on random walk technique in order to optimize the movement between one node to another over a graph [43, 44]. A novel subMarkov random walk (subRW) framework was proposed in [43] to unify four different random walk based algorithms. The current node walks out to other nodes along the edges connected with it while using a certain probability, where the random walker is transformed to a random walker with Markov transition probability.

Table 1 provides a summary of the above-discussed related works, which highlight the different forwarding mechanisms used by the investigated protocols/schemes. It also shows the protocols/schemes as either adopting a *sender-oriented* or a *receiver-oriented* next-hop relay nodes selection mechanism, where most of them consider the *sender-oriented* due to its capability in providing controlled rebroadcasts, hence facilitating an efficient utilization of the available spectrum.

Table 1: Comparative study for the main features exhibited by the investigated VANETs protocols/schemes.

Protocol / Scheme	**Traffic awareness**	**Forwarding mechanism**	**V2V/ V2I**	**Simulation Scenario**	**Application**	**Sender/Receiver oriented relaying**
PIVCA *[17, 36]*	Yes	Furthest distance	V2V	Highway	Infotainment and safety services	Receiver-oriented
Oracle *[16]*	Yes	Furthest transmission range	V2V	Highway	Safety services	Sender-oriented
MCROB *[19]*	Yes	Expected transmission speed	V2V	Highway	Safety services	Sender-oriented
Selective forwarding *[25]*	Yes	Distance and relative velocity	V2V	Highway	Safety services	Sender-oriented
Path diversity *[35]*	Yes	Can be incorporated with different forwarding mechanisms	V2V	Highway and Urban	Infotainment and safety services	Sender-oriented
DEEP *[12]*	Yes	Combination of multiple algorithms w.r.t. distance from source	V2V & V2I	Highway	Safety services	Receiver-oriented
EPD *[20]*	Yes	Distance and forward / reverse links quality	V2V	Highway	Infotainment	Sender-oriented
GreeAODV *[37]*	Yes	Energy efficiency	V2V	Urban	Safety services	Sender-oriented
CPB *[27]*	Yes	Clustering and probabilistic broadcasting	V2V	Highway	Infotainment and safety services	Receiver-oriented
BDSC *[21-23]*	Yes	Distance and forward link quality	V2V	Highway	Infotainment and safety services	Sender-oriented

3. Base Components of Hybrid Scheme

This section provides a brief description of the BDSC scheme and its variants [21-23], which represents a major building block in the devised hybrid scheme. The BDSC scheme has been designed with a particular focus on safety-related applications and for the case of multi-lane and strip-shaped roads structures as one of the major potential application of VANETs [1]. The BDSC scheme is composed of three operation layers, namely the "*HELLO* packets exchange" "Link Quality Estimation" and the "Link Selection" layers, where the following subsections provide descriptions of the three stated layers. In addition, the last subsection is devoted to discuss the details of *sender-oriented* relay nodes selection mechanism that is adopted for the proposed hybrid scheme.

Before going into the details of the above described points, the forward/reverse links concept is clarified at this stage for further usage in the manuscript. In a given pair of nodes, each node has two communication links with the other, more specifically the forward and reverse links [24]. While considering the example of a pair of nodes *A* and *B*, the communication link from *A* to *B* is considered as the forward link of *A*, while the communication link from *B* to *A* is the reverse link for node *A*. In the remaining parts of this paper, the terms "vehicle" and "node" will be used interchangeably as seen best fit within the context. In addition, the terms "packet" or "*HELLO* packet" will be referred to the periodically generated beacons, while "message" will be used when referring to application specific data that are generated for multi-hop propagation; such as an alert message.

3.1 *HELLO* Packets Exchange Layer

Initiated by each node in the VANETs, single-hop neighboring nodes information are exchanged with the assistance of periodic broadcasts of *HELLO* packets. The exchange of information is limited to single-hop nodes, which is considered as sufficient for a given node to get acquainted with the surrounding nodes condition [16, 17]. The information embedded inside each *HELLO* packet contains the source node's ID, positioning coordinates and an updated list of directly connected vehicles, referred to as the active communication nodes list (ACNL). A given source node's ID can be represented by the MAC address of the IEEE-802.11-based transceiver, and the positioning coordinates can be taken with assistance of satellite system based receivers, such as receivers for the Global Positioning System (GPS) or Global Navigation Satellite System (GNSS) [45]. On the other hand, the ACNL is built locally at each node as a result of using the nodes IDs extracted from the received *HELLO* packets. At each node, the ACNL is reset after the broadcast of each *HELLO* packet, while being updated between every two consecutive *HELLO* packets broadcast.

3.2 Link Quality Estimation Layer

In conventional vehicular communication scenarios, the broadcasting source cannot be aware of the number of *HELLO* packets that were successfully received at the other nodes, unless acknowledged by the receiving nodes. However, explicitly acknowledging the reception of the broadcast packets can easily lead to the well-known broadcast storm problem. In order to resolve this problem, the BDSC scheme introduces an implicit acknowledgement mechanism for the successfully received *HELLO* packets over the forward links. The proposed mechanism runs locally in each node at the "Link Quality Estimation" layer by which quantitative representations of the forward link qualities are obtained.

Implicit acknowledgement for the successfully received *HELLO* packets is achieved by taking assistance of the ACNLs (discussed in Section 3.1) that are incorporated inside the *HELLO* packets. For each *HELLO* packet reception, the receiving node scans the ACNL for its own ID. In case the node finds its ID within the ACNL, the node realizes that its last sent *HELLO* packet was heard by the current sender, which in-turn is an implicit acknowledgment. As a result, the corresponding implicit acknowledgement count (IAC) for that link is increased by one. In contrast, the *HELLO* packet is discarded and IAC is not incremented if the implicit acknowledgement condition is not satisfied. The expected number of *HELLO* packets within the time duration T_{BDSC} is defined by T_{BDSC}/T_h, where T_h is the time interval between consecutive broadcasts of *HELLO* packets. The forward link quality (LQ) between a pair of nodes is expressed by $LQ = IAC/(T_{BDSC}/T_h)$, where higher values of LQ indicate better quality of the communication link. Estimation of the forward link quality is a periodic process that takes place after every time period T_{BDSC}. Within the time period T_{BDSC}, acceptance or rejection of the received *HELLO* packets for the process of link quality estimation is carried based on the above described algorithm. In this work, a system configuration of $T_{BDSC} = 5$ sec is considered, which is also similar to those adopted in other relevant research work [20].

A message flow sequence depiction of the implicit acknowledgement process between a given pair of nodes *A* and *B* is presented by Figure 3. While focusing on node *A*, the first increment in the IAC occurs due to the successful reception of the *HELLO* packet at node *B* (transmitted by node *A*), and then immediately followed by the successful reception of the *HELLO* packet at node *A* (transmitted by node *B*). Similar patter can be followed for the third *HELLO* packet transmitted from node *A*. In contrast, loss of the second *HELLO* packet transmitted from node *A* leads towards the absence of an increment in IAC at node *A*.

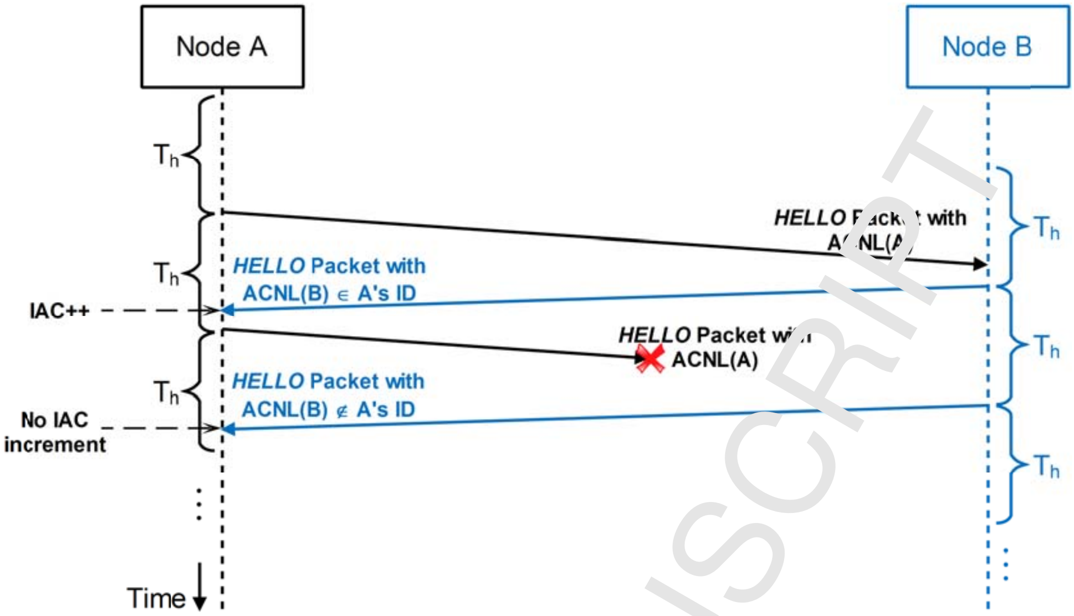


Figure 3: Message sequence chart depicting the implicit acknowledgement of the broadcasted *HELLO* packets in the BDSC scheme.

3.3 Link Selection Layer

The third layer in the BDSC scheme is the "Link Selection" layer which prioritizes links, hence nodes, for rebroadcasting the received messages. Based on the chosen link selection policy, as described briefly below and in more details in [21-23], the broadcasting node selects a set of links representing potential relay nodes and includes their IDs in the broadcasted messages. The "Link Selection" layer is dependent on feedback received by the "Link Quality Estimation" layer, as a consequence the dynamic updates of link qualities occurring every time T_{BDSC} will have a direct impact on the selected relay nodes at the time of message broadcast. Two adaptive link selection criteria are discussed in this paper as described below.

3.3.1 Iterative Link Search

The "Iterative Link Search" algorithm searches for all the links that satisfy the $LQ \geq Th$ condition, where Th is a predefined system parameter depicting a threshold value. While employing a *sender-oriented* relay selection mechanism, the algorithm checks if all C relay choices are filled at end of the searching process, and if not, the current threshold Th scale is reduced by a magnitude of 0.1 resulting in a new defined $LQ \geq Th$ condition. Based on the new defined threshold scale, a search for new links that satisfy the new condition takes place while avoiding those that already have been selected. This process stops when either all C nodes choices have been fulfilled or the threshold $Th < 0$ condition is reached or that all available link options have been exhausted. In each search iteration, once the useful nodes are identified, the nodes falling furthest in distance from the source are given higher priority for relaying with the aim of reducing the end-to-end delay. The selected nodes are sorted in a descending order according to their distance from source, where the sorting process at each iteration excludes the nodes that were selected in the previous iterations. For the purpose of this study, a link selection condition defined as the threshold $Th = 1.0$ is adopted for the "Iterative Link Search" algorithm which depicts the selection of links that have the highest link quality ratios. The $Th = 1.0$ condition aims to improve message dissemination reliability measured in-terms of messages reachability.

3.3.2 Distance to Link Quality

This algorithm defines a composite metric based on the estimated link qualities of neighboring nodes with the source and their corresponding distances d, determined by the product $LQ \times d$. The product gives a new quantitative metric which attempts to strike a balance between the link qualities and the progress distances from the source. Among the C selected links, hence nodes, a higher priority is given to those links with larger product values. For this work, the maximum considered distance d from the sender is defined by the configured transmission range R for the wireless transceiver, which is adopted as 300m for this research [46]. In the "Distance to Link Quality" algorithm, the product value increases as both LQ and d increases. However, a higher link quality does not imply having a larger product value out of $LQ \times d$, since d can also largely effect the end product. As a naming convention, the “Iterative Link Search” with $Th = 1.0$ and the “Distance to Link Quality” criteria will be referred hereafter as BDSC ($Th = 1.0$) and BDSC ($LQ \times d$), respectively.

4. The Hybrid Scheme

The concept of hybrid relay nodes selection is introduced in which different message dissemination schemes are exploited to devise a new class of schemes. While adopting the *sender-oriented* mechanism, the hybrid scheme attempts to combine the best features of existing messaging schemes while suppressing their shortcomings. Structure of the *sender-oriented* mechanism incorporated within the proposed hybrid scheme is as follows. The list of IDs representing the contending next-hop relay nodes are constructed at the sender side and referred to as “relay priority list” [21-23], where each entry in the list is represented as a “slot”. In order to obtain a rebroadcast priority among the C contending relays, the entries inside the “relay priority list” are assigned with prioritization indexes, referred to as the “relay priority index”, i. A given relay with highest rebroadcast priority is assigned with the lowest index value, and vice versa is correct. At the time of message dissemination, the constructed “relay priority list” is incorporated inside the message, then transmitted to the neighboring nodes. At the receiver side, those nodes that receive the broadcast messages but do not find their IDs inside the “relay priority list” do not contend for becoming a next forwarder. If ID of a receiving node is within the received list, the receiver sets its rebroadcast waiting time, referred to as “relay waiting time”, proportional to the “relay priority index” of the node’s ID. The “relay waiting time” is the product of “relay priority index”, i, with a pre-defined waiting slot duration of α msec, and is given by $t_i = i \times \alpha$, where $i = 0, \dots, C-1$. Once one of the explicitly selected relays rebroadcasts the message, all other contending nodes will stop their waiting process once hearing that rebroadcast. By setting up an appropriate waiting time difference between the contending relays, a rebroadcasting priority is inherently achieved, leading towards the reduction of redundant rebroadcasts and hence high efficiency in bandwidth utilization [21-23].

4.1 Design Principles of Hybrid Scheme

This section explores several attributes of the conventional FD and BDSC schemes, as the building blocks for the hybrid scheme. This step is considered to utilize these attributes as design principles for the proposed hybrid scheme. Even though this research exploits FD and BDSC schemes only, the suggested principles can be used as guidelines while considering any other set of message dissemination schemes. This section also presents and discusses the behavior patterns of the attributes under investigation, which are taken as the basis for devising the ordered-combinations in the hybrid scheme. These performance patterns were previously observed for the investigated schemes when evaluated over different simulation environments [21, 22]. Since similar performance patterns were obtained for the schemes under investigation, hence we can infer that the obtained patterns can be generally endorsed to the investigated schemes without being significantly influenced by the adopted simulation setup. Details of the investigated attributes along with behavior patterns are given in the following subsections.

4.1.1 Link Quality

The link qualities between a given source and the potential relay nodes assists in predicting the probability for a transmitted message to successfully reach the relays. In this research, the estimated forward link quality is considered as the quantitative representation for the probability of message reception [22], in which higher link quality indicates greater probability of reception and vice versa is correct. The link quality is mainly affected by the distance between the source and the receiver, surrounding nodes density and adverse propagation channel effects. More precisely, larger distance, denser network and higher channel fading intensity results in higher loss of the exchanged *HELLO* packets and hence lower link qualities are obtained.

The FD and BDSC schemes are studied for their link quality patterns. Though FD does not adopt any link quality estimation concept, the link quality estimated for the FD scheme is based on that obtained through the algorithm used for the BDSC scheme. Details on the link qualities obtained for FD and BDSC schemes can be found in our previous works [21-23], while this section would present their main findings. In FD, it is of interest to know that as the node density increases, nodes selected as relays exhibit the lowest link quality ratios when compared to those obtained by BDSC ($Th = 1.0$) and BDSC ($LQ \times d$) schemes. The BDSC ($Th = 1.0$) exhibits the highest link quality, while the BDSC ($LQ \times d$) is known to exhibit better link qualities to those obtained by FD but lower than those obtained by BDSC ($Th = 1.0$). Though it can be generally stated that higher link quality implies an improvement in message reachability, but the same cannot be said for BDSC ($Th = 1.0$) which has been known to exhibit poor reachability and high end-to-end delays as the node density increases due to the large hop counts required for reaching a targeted destination [22].

4.1.2 Spatial Distribution of Relay Nodes

In this research, the spatial distribution is defined as an estimated separation distance between the current source and the set of next-hop potential relays nodes. This estimated distance is calculated as the average distance between the source node and the selected C relay nodes. The average distance is calculated according to each relay node's contribution in forwarding the received messages among the set of C relay nodes, and is given by $\bar{d} = (\sum_{i=1}^{C} w_i d_i)$, where w_i is the relaying contribution of node i, in percentage, and d_i is the actual distance in meters of node i from the source.

The main findings obtained previously for the investigated FD and BDSC scheme are as described next [21-23]. The FD scheme selects those nodes as relays that fall farthest in distance from the source, which reduces the required hop counts to reach a targeted destination and hence the overall end-to-end delay [16, 22]. In contrast, the BDSC ($Th = 1.0$) selects those nodes that fall nearest in distance from the source, which in-turn results in large hop counts to reach a desired node, hence increasing the end-to-end delay. Finally, the BDSC ($LQ \times d$) scheme attempts to adaptively strike a balance between distance and link quality rather than considering only a single factor. In BDSC ($LQ \times d$), the nodes selected as relays fall far in distance from the source when the surrounding node density is low, while tending to become closer to the sender as the node density increases [21, 23]. The working phenomenon of the BDSC ($LQ \times d$) scheme results in low hop count requirements and low end-to-end delays at low node density VANETs, while having a small and smooth increments in hop counts, hence in end-to-end delay, as the node density increases [21, 23].

In FD scheme, the distance of the selected relay nodes from the sender exhibits a rise as the node density increases. This occurs since more nodes are present within a specific broadcast area as the node density increases, which in-turn increases the probability of finding relays farther in distance as compared to that in lower node density VANETs. The BDSC ($LQ \times d$) and BDSC ($Th = 1.0$) schemes tends to select relays closer in distance from the source as the node density increases, since nodes fulfilling the conditions of these two schemes tend to become closer to the source with increase in node densities.

4.1.3 Performance of Messaging Schemes

Performance of the investigated message dissemination schemes is measured in terms of messages reachability, end-to-end delay and saved rebroadcast over both low and high node density VANETs [21-23]. It is of importance to comprehend these three performance behaviors of the examined message dissemination schemes to be able to device an effective hybrid scheme. The performance study of different message dissemination schemes assists in deciding upon which messaging scheme is best fit to be used for a given slot in the "relay priority list" of the *sender-oriented* relay nodes selection.

The FD scheme is known to exhibit low end-to-end delay along with having high saved rebroadcast [16, 17, 22] but at the cost of poor reachability performance over high node density VANETs [22]. However, it is realized that over high node density VANETs, the end-to-end delay tends to increase noticeably in the FD scheme as the relative speed difference among the nodes increases [22]. On the other hand, BDSC ($Th = 1.0$) exhibits the highest link qualities, but poor reachability performance is exhibited as the node density increases. This is due to the length of the communication path a source node has to traverse to reach the destination, where the success and failure probabilities of a message's propagation at each hop would affect the following ones. In contrast to the situations over high node density VANETs, higher reachability is noticed by BDSC ($Th = 1.0$) at low node densities when compared with FD and BDSC ($LQ \times d$) [22]. Furthermore, high end-to-end delay is exhibited by BDSC ($Th = 1.0$) along with low saved rebroadcasts, which become more prominent as the node density increases. Finally, the BDSC ($LQ \times d$) scheme exhibits the best reachability performance, especially over high node densities, while showing competitive end-to-end delay and saved rebroadcast to those obtained by FD.

4.1.4 Relay Nodes Contribution

The relaying contribution of each relay node, among the group of C contending nodes, is suggested to be studied in our previous works [21-23]. The relaying contribution provides an insight on the involvement of each relay in rebroadcasting the received messages while employing a given scheme. This would assist in determining the usage frequency of a given message dissemination scheme within the devised hybrid scheme. Computation of relaying contribution for each relay node is performed by counting the number of cases where a given relay has indeed relayed the message. For an end-to-end communication scenarios that occurs over H hop counts, the relaying contribution is computed by $R_i = H_i/H$, where $H_i = 0, \ldots, H$ and H_i is the number of times a given message was relayed by a relay node having the "relay priority index" i.

For the investigated FD and BDSC schemes, it is deduced that those relay nodes having the "relay priority index" $i = 0$ exhibit the highest contribution in relaying the received messages, when compared with all other contending C relays [22]. Furthermore, more than 80% of relaying is performed by relays with "relay priority indexes" ranging from $i = 0\ to\ 2$, which represent most of the relaying contribution [22]. Based on the described observations, it is aimed to exploit the maximum potential of the messaging schemes over the first three relays within the "relay priority list", i.e. for relays with "relay priority indexes" ranging from $i = 0\ to\ 2$, when devising the hybrid scheme. This is due the fact that effective combinations applied for the first three slots will most likely have a potential impact on performance of the hybrid scheme.

4.2 The Ordered-Combination in Hybrid Scheme

The attributes discussed in Section 4.1 are considered to determine the ordered-combinations of the conventional FD and BDSC schemes, which are utilized for devising the proposed hybrid schemes. These attributes determine the combination of the exploited message dissemination schemes, their order and usage frequency while preparing the "relay priority list". Two variants within the hybrid scheme are proposed, each having a different ordered-combination of the exploited conventional schemes. In the conventional techniques, the group of relay nodes are selected at each message broadcast based on a single message dissemination scheme.

In this section, we introduce the concept of choosing the set of relay nodes based on different messaging schemes. Each node within the "relay priority list" can be chosen based on a different message dissemination scheme. In addition, a given message dissemination scheme can be used multiple times for selecting the relays within the group of C selected nodes. The proposed two variants of the hybrid schemes attempt to further improve the reachability performance over that obtained by the competitor BDSC ($LQ \times d$) and FD schemes at both low and high node density networks [21, 23]. The two proposed variants of the hybrid scheme is referred to from this point onwards as Hybrid (FD) and Hybrid ($LQ \times d$).

4.2.1 Hybrid (FD) Scheme

The goal of the first variant in the proposed hybrid relay selection scheme is to obtain low end-to-end delays, similar to those obtained by the conventional FD scheme, while improving reachability performance over that obtained by BDSC ($LQ \times d$). By keeping these objectives in mind, the first proposed hybrid scheme, referred to as Hybrid (FD), exploits FD, BDSC ($LQ \times d$) and BDSC ($Th = 1.0$) in a combination depicted by Figure 4. The Hybrid (FD) naming convention is adopted since the first slot within the "relay priority list" of the proposed scheme is always occupied by a relay node selected based on the FD scheme.

In order to obtain low end-to-end delay, Hybrid (FD) assigns the first slot in the "relay priority list" with a node ID while exploiting the FD scheme, which in-turn selects the ID of the farthest node in distance. However, the messages disseminated using the FD scheme is highly likely to be lost over the propagation channel which in-turn causes a drop in reachability. To compensate for the reachability shortcomings exhibited by FD, the Hybrid (FD) assigns the second slot in the "relay priority list" with a relay node ID based on BDSC ($LQ \times d$). In-fact, by employing BDSC ($LQ \times d$) for the second slot within the "relay priority list", the Hybrid (FD) attempts to maintain low end-to-end delays besides improving reachability.

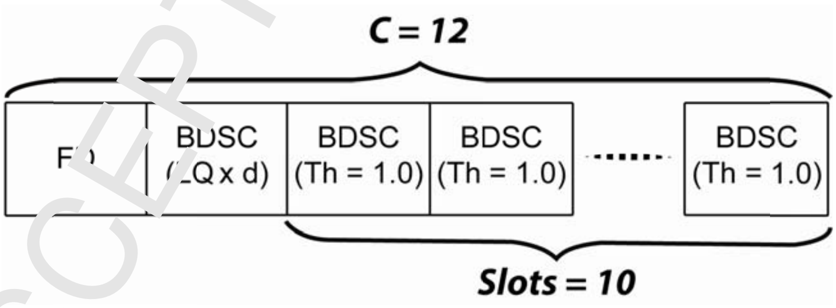


Figure 4: The ordered-combination in Hybrid (FD) scheme.

As discussed in Section 4.1.2, BDSC ($Th = 1.0$) portrays the selection of nodes that are near in distance to the sender, resulting in relay nodes selection having high probability of successful messages reception. However, BDSC ($Th = 1.0$) suffers from loss of the broadcasted messages and rapid increase in end-to-end delays if the same technique is utilized repeatedly over each hop. Therefore, BDSC ($Th = 1.0$) is utilized with the proposed Hybrid (FD) scheme as a recovery technique for the cases in which the first and second relay nodes listed in the "relay priority list" fail to relay the broadcast message. In effect, the Hybrid (FD) scheme assigns the third and the onward slots in "relay priority list" with a relay nodes IDs based on BDSC ($Th = 1.0$).

While summarizing the working mechanism of Hybrid (FD), the FD scheme attempts to reduce the end-to-end delay, the BDSC ($LQ \times d$) attempts to compensate the messages loss by FD while also maintaining low end-to-end delay and lastly, BDSC ($Th = 1.0$) attempts to recover the loss suffered by relays selected using the previous two schemes. At each hop, the message broadcast maintains the same combination in the Hybrid (FD) scheme, hence always promoting the furthest in distance node as its first option. While observing the devised combination in Figure 4, a spatial distribution in relay nodes selection is obtained by the proposed combination in Hybrid (FD). This is realized by the fact that the first selected node in the "relay priority list" would fall furthest in distance from the source, while the second would be comparatively nearer in distance and the last ten nodes would be the nearest in distance. This is opposed to the conventional FD scheme in which all selected relay nodes would likely be the ones that are furthest in distance from the source.

4.2.2 Hybrid ($LQ \times d$) Scheme

As it is discussed in Section 4.1.3, the end-to-end delay tends to increase noticeably, while adopting the FD scheme, as the relative speed difference among the nodes increased. As a consequence, it is likely that Hybrid (FD) will exhibit an increase in the end-to-end delay over speed scenarios having high relative speed difference among the nodes, which is due to the adoption FD scheme for its first slot within the "relay priority list". In an effort to rectify the problem, this section proposes a new variant for the hybrid scheme, referred to as Hybrid ($LQ \times d$), where its composition is presented by Figure 5. The Hybrid ($LQ \times d$) differs with Hybrid (FD) only by adopting BDSC ($LQ \times d$) for the first relay slot within the "relay priority list", which is also the reason behind its naming convention. In general, Hybrid ($LQ \times d$) aims at similar goals to those by the Hybrid (FD) but while being more effective over mobility models with high relative speed difference.

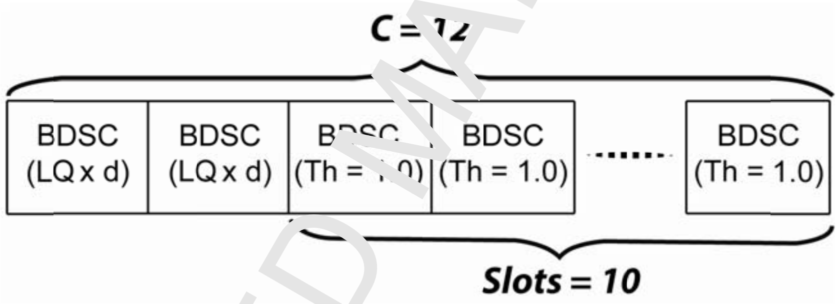


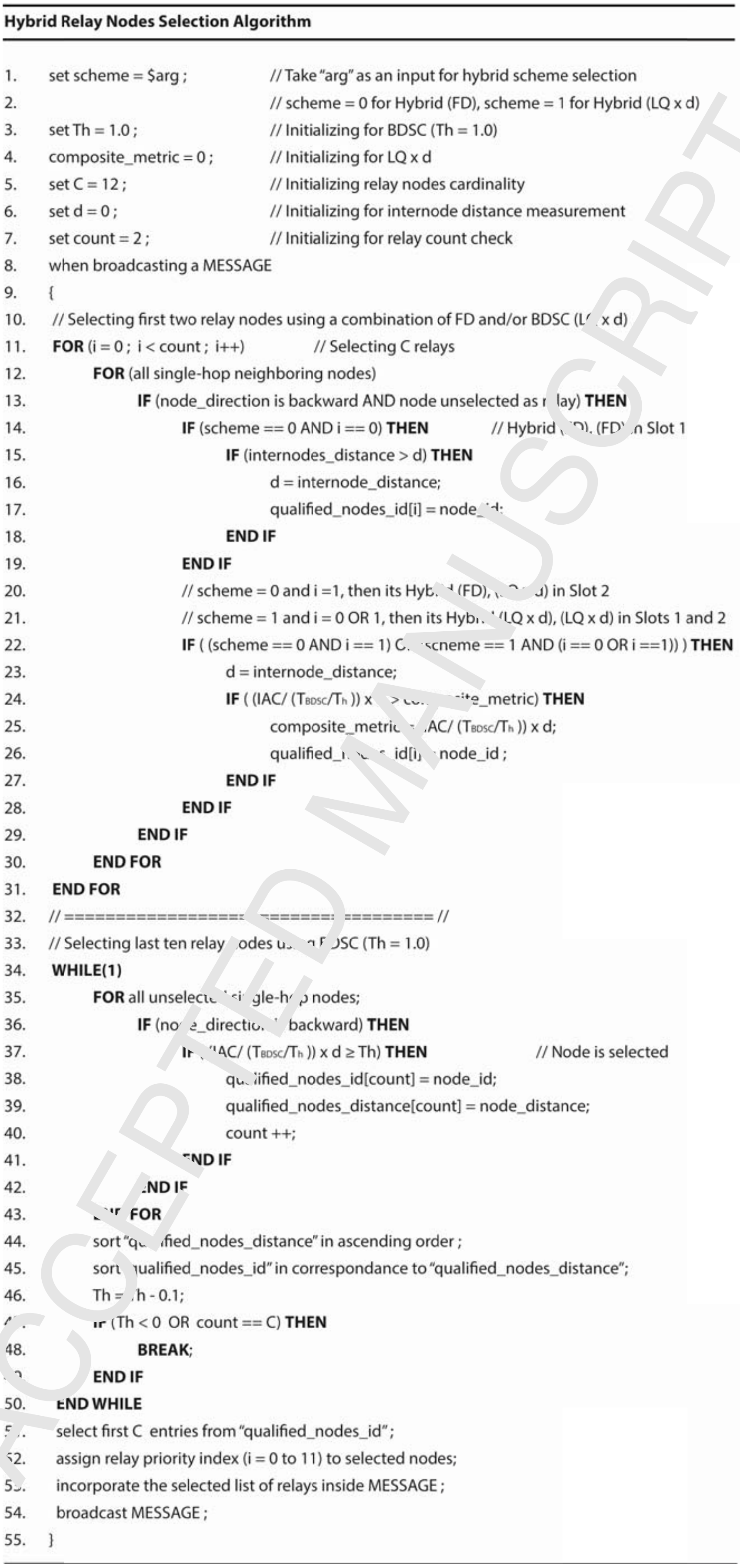
Figure 5: The ordered-combination in Hybrid ($LQ \times d$) scheme.

4.2.3 Pseudo Code of Hybrid Scheme

Algorithm 6 gives a pseudo code representing both proposed variants within the hybrid scheme. The given pseudo code is mainly divided into two parts. The first part, as given in Lines 10 – 31, represents the selection of the first and second relay nodes within the slots of "relay priority list" and while exploiting the FD and BDSC ($LQxd$) schemes. The second part, as given in Lines 33 – 50, represents the selection of the remaining ten slots within the "relay priority list" and while exploiting the BDSC ($Th = 1.0$) scheme. Details regarding the operation of the proposed hybrid schemes represented by the pseudo code is as follows:

- The program initially selects which variant of the two proposed hybrid schemes to use for messages dissemination, i.e. either Hybrid (FD) or Hybrid ($LQxd$) This is decided based on the input argument "$arg", as represented by Line 1. A value of 0 indicates the selection of Hybrid (FD), while a value of 1 indicates the selection of Hybrid ($LQxd$).
- Initialization of several variables involved in the algorithm takes place in Lines 3 – 7, including the setup of relay nodes cardinality to a value of $C = 12$.
- Selection of the first and second relay nodes within the slots of "relay priority list" is given in Lines 10 – 31. In both proposed variants of the hybrid scheme, the first and second relay nodes are selected by exploiting the conventional FD and BDSC ($LQxd$) schemes.
- For the proposed Hybrid (FD), the first relay node within the slots of "relay priority list" is selected by the FD conventional scheme as depicted by Lines 14 – 19. While the second relay node is selected by the BDSC ($LQxd$) conventional scheme as depicted by Lines 22 – 28.

- For the proposed Hybrid ($LQxd$), the first and second relay nodes within the slots of “relay priority list” are selected by the BDSC ($LQxd$) conventional scheme as depicted by Lines 22 – 28.
- For both proposed Hybrid (FD) or Hybrid ($LQxd$) schemes, the last ten nodes within the “relay priority list” and are selected while exploiting the BDSC ($Th = 1.0$) scheme, as depicted by Lines 32 – 50.
- The IDs of $C = 12$ selected relay nodes are provided along with their priority indexes $i = 0\ to\ 11$. The list is incorporated into the broadcast message to be sent further upstream, as represented by Lines 51 – 54.



Hybrid Relay Nodes Selection Algorithm

```
set scheme = $arg ;                 // Take "arg" as an input for hybrid scheme selection
                                    // scheme = 0 for Hybrid (FD), scheme = 1 for Hybrid (LQ x d)
set Th = 1.0 ;                      // Initializing for BDSC (Th = 1.0)
composite_metric = 0 ;              // Initializing for LQ x d
set C = 12 ;                        // Initializing relay nodes cardinality
set d = 0 ;                         // Initializing for internode distance measurement
set count = 2 ;                     // Initializing for relay count check
when broadcasting a MESSAGE
{
 // Selecting first two relay nodes using a combination of FD and/or BDSC (LQ x d)
 FOR (i = 0 ;  i < count ;  i++)              // Selecting C relays
     FOR (all single-hop neighboring nodes)
         IF (node_direction is backward AND node unselected as relay) THEN
             IF (scheme == 0 AND i == 0) THEN             // Hybrid (FD), (FD) in Slot 1
                 IF (internodes_distance > d) THEN
                     d = internode_distance;
                     qualified_nodes_id[i] = node_id;
                 END IF
             END IF
             // scheme = 0 and i =1, then its Hybrid (FD), (LQ x d) in Slot 2
             // scheme = 1 and i = 0 OR 1, then its Hybrid (LQ x d), (LQ x d) in Slots 1 and 2
             IF ( (scheme == 0 AND i == 1) OR (scheme == 1 AND (i == 0 OR i ==1)) ) THEN
                 d = internode_distance;
                 IF ( (IAC/ ($T_{BDSC}/T_h$ )) x d > composite_metric) THEN
                     composite_metric = (IAC/ ($T_{BDSC}/T_h$ )) x d;
                     qualified_nodes_id[i] = node_id ;
                 END IF
             END IF
         END IF
     END FOR
 END FOR
// ======================================================== //
// Selecting last ten relay nodes using BDSC (Th = 1.0)
 WHILE(1)
     FOR all unselected single-hop nodes;
         IF (node_direction is backward) THEN
             IF ((IAC/ ($T_{BDSC}/T_h$ )) x d ≥ Th) THEN                // Node is selected
                 qualified_nodes_id[count] = node_id;
                 qualified_nodes_distance[count] = node_distance;
                 count ++;
             END IF
         END IF
     END FOR
     sort "qualified_nodes_distance" in ascending order ;
     sort "qualified_nodes_id" in correspondance to "qualified_nodes_distance";
     Th = Th - 0.1;
     IF (Th < 0  OR  count == C) THEN
         BREAK;
     END IF
  END WHILE
  select first C  entries from "qualified_nodes_id" ;
  assign relay priority index (i = 0 to 11) to selected nodes;
  incorporate the selected list of relays inside MESSAGE ;
  broadcast MESSAGE ;
}
```

Algorithm 1: A pseudo code representation of the Hybrid (FD) and Hybrid ($LQxd$) schemes.

5. Simulation Environment

Throughout this research, the following assumptions are considered which have been widely adopted in similar studies [12, 16-18, 35, 36]. A single-way, multi-lane and strip-shaped road segment is considered where all vehicles move in the same direction. Nodes travelling in the same direction results in links with longer connectivity duration as compared to nodes travelling at opposite directions over a two-way road segment. Having a higher link life implies a higher contention between the neighboring nodes due to their periodically exchanged *HELLO* packets. The single-way road scenario assists in evaluating the proposed hybrid scheme over high contention channel. Furthermore, all vehicles are assumed to be equipped with the necessary hardware devices required for the operation of the hybrid scheme, namely a wireless transceivers adhering to the IEEE 802.11p standard [16, 17], a positioning device such as GPS or GNSS based receivers and a data processing unit. The Network Simulator 2.35 (ns-2) is used as the simulation platform, where the main modifications performed in the IEEE 802.11 standard is the usage of carrier frequency of 5.9 GHz and a control channel bandwidth of 10 MHz, to adhere with the recommended IEEE 802.11p standard for vehicular communications. It is also assumed that node ID's are represented by a single alphabetical letter within the simulation environment, while any addressing scheme can be adopted in real-life scenarios.

The adopted relay node cardinality is $C = 12$ [47]. The proposed hybrid scheme is designed to work in compatibility with the control channel of the IEEE 802.11p-based transceivers of the DSRC technology. The transceivers are configured for 300 meters transmission range, as recommended in the IEEE 802.11p standard. Furthermore, The evaluations are performed over the Two-Ray Ground reflection channel model as the most commonly adopted wireless propagation channel model in VANETs [12, 16-18]. A simulation time of 130 seconds is assigned for each simulation run in which performance of the hybrid scheme is evaluated, where the results are averaged over 40 simulation runs.

The mobility models are identified in literature as influencing factors on performance of message dissemination schemes in VANETs, especially on the link life among neighboring nodes and network partitioning [48]. Therefore, two mobility speed ranges are considered to evaluate performance of the proposed hybrid scheme that represent widely adopted speed scenarios in literature for VANETs [12, 16, 17, 49]. The speed scenarios adopted range from 95-105 km/h and 80-140 km/h. The former represents a small relative speed difference of 10 km/h among the nodes, resulting in a platoon of vehicles with nodes distributed in close proximity to each other. The later represents a higher relative speed difference among the nodes that results in nodes being positioned much farther from each other when compared to the 95-105 km/h scenario. In both speed scenarios, each node is randomly assigned with a mobility speed within the considered speed range which remains constant throughout the simulation time period. Performance evaluation over different mobility speeds can reveal different performance trends for any investigated schemes, in which the proposed hybrid scheme should be of no exception. In-fact, limiting performance evaluation over a single speed scenario can imposes a limitation on understanding the performance behavior of the hybrid scheme.

A platoon of varying network densities ranging from 50 to 600 nodes are considered, while adopting an increment of 50 nodes per simulation scenario. Coverage area of the platoon varies as a function of the total node densities and the employed speed scenario. Initially, vehicles are uniformly distributed over an approximately 4 km highway segment. The highway road is a three lanes strip shaped road segment with each lane of 3.7 meters in width and all vehicles are of 4m in length. Based on the above defined parameters, the node density per kilometer representation is given as approximately 12 nodes/km for a 50 nodes network, and approximately 150 nodes/km for the case of 600 nodes network. The 4 km road segment containing the platoon of vehicles is part of a 20 km highway road over which the vehicles move throughout the 130 seconds of simulation time. At each simulation run, the platoon of vehicles is placed at the beginning of the 20 km road. Based on the two adopted speed scenarios, the maximum distance that any given vehicle would cover in the considered simulation time is approximately 5 km. As a result, all moving vehicles would stay within the maximum defined limit for the 20km highway road.

Two types of broadcasts are considered which are represented by *HELLO* packets broadcast and the multi-hop application messages broadcasts. In order to analyze the impact of varying network traffic load on the proposed hybrid scheme, two different *HELLO* packets broadcast frequencies are adopted, namely 10 packets/second and 2 packets/second. Since all nodes are initially distributed uniformly over a 4 km road segment, the first 60 seconds are given for the nodes to get distributed over the adopted topography. At the start of the next 60 seconds, the first (source node) and the last (destination node) nodes in the platoon are dynamically identified by the simulator. This is followed by the multi-hop application messages by broadcasted periodically with a frequency of 10 messages/second, that are initially generated by the source node. Broadcast of the application messages start after the passage of 60 seconds of simulation and continues for the next 60 seconds. The last 10 seconds of simulation is given for the messages within the platoon to complete its propagation process for reaching the desired destination, i.e. the last node in the platoon. Furthermore, a size of 512 and 256 bytes are chosen for the broadcasted *HELLO* packets and application messages, respectively. A summary of the main parameters used in our simulation experiments are presented in Tables 2 while Table 3 lists the system parameters adopted for the IEEE 802.11p standard.

Table 2: System parameters.

Parameter	*Value*
Total node density	50 – 600 nodes (increment of 50 nodes)
HELLO packet size	512 Bytes
Application message size	256 Bytes
HELLO packet frequency	10 packets/sec 2 packets/sec
Application message frequency	10 messages/sec
Antenna type	Omni-directional
Transmission range	300 m
Simulation runs	40 runs
Simulation time	130 seconds (warm-up 60 sec; messages dissemination 60 sec; flushing messages in queue 10 sec)

Table 3: IEEE 802.11p parameters.

Parameter	*Value*
Frequency	5.9 GHz
Channel bandwidth	10 MHz
Data rate	6 Mbps
Slot time (σ)	16 µsecs
SIFS time	32 µsecs
Preamble length	32 µsecs
PLCP header length	8 µsecs
CW_{min}	32 slots
CW_{max}	1024 slots

6. Attributes Analysis of Hybrid Scheme

Before discussing the performance results, this section presents and analyzes the attributes exhibited by the hybrid scheme, along with comparing them to those obtained by the building blocks, i.e. FD and BDSC schemes. The attributed discussed in this section are those adopted as the design principles for devising the hybrid scheme, as discussed previously in Section 4.1. These attributes are analyzed according to the simulation environment adopted and discussed in Section 5. In this work, the attributes study has been limited to traffic load condition of 10 $HELLO$ packets/sec, which is a more stringent communication environment as compared the 2 $HELLO$ packets/sec scenario. These analyses would assist in comprehending the performance results obtained by the hybrid scheme, as presented in the next section.

The link quality attributes of the two variants with in the hybrid scheme, i.e. Hybrid (FD) and Hybrid ($LQ \times d$) is presented by Figure 6 (a) and (b) for the two considered 95-105km/h and 80-140 km/h speed profiles, respectively. The figure also presents those attributes for the conventional FD, BDSC ($LQ \times d$) and BDSC ($Th = 1.0$) schemes that have already been mentioned in Section 4.1.1. In Figure 6, the Hybrid (FD) scheme exhibits a higher link quality when compared against the conventional FD scheme over high node density networks. This is due to the relaying contribution of those nodes that are selected based on BDSC ($LQ \times d$) and BDSC ($Th = 1.0$), as depicted by the ordered-combination of Hybrid (FD) scheme in Figure 4. On the other hand, a marginal rise in link quality is exhibited by the Hybrid ($LQ \times d$) scheme when compared against the conventional BDSC ($LQ \times d$) scheme, which occurs due to the relaying contribution by nodes selected based on BDSC ($Th = 1.0$), as depicted by the ordered-combination of Hybrid ($LQ \times d$) scheme in Figure 5.

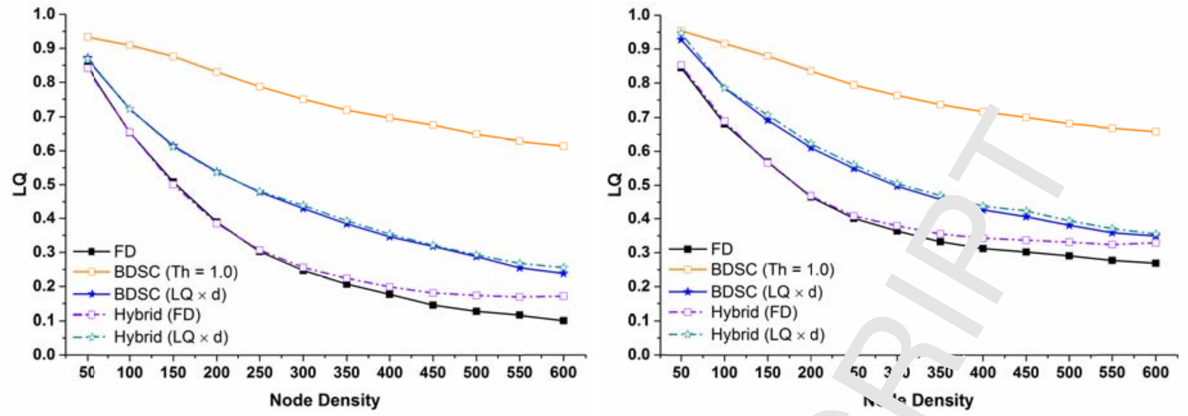


Figure 6: Estimated link quality ratios obtained by the hybrid schemes as a function of node density and with mobility speed ranges (a) 95-105 km/h (b) 80-140 km/h.

The spatial distribution attributes of FD and BDSC schemes have already been elaborated in Section 4.1.2, and is presented along with those for the hybrid schemes in Figures 7 (a) and (b) over the 95-105 km/h and 80-140 km/h speed scenarios, respectively. Through Figure 7, it can be observed that varying spatial distribution patterns are exhibited by the hybrid schemes when compared to the conventional schemes, which becomes even more prominent as the node density increases. The Hybrid (FD) and Hybrid $(LQ \times d)$ exhibit spatial distributions that is closer in distance from the source when compared to their conventional counterparts, i.e. FD and BDSC $(LQ \times d)$, respectively. This is due to the relaying contribution by nodes selected based on BDSC $(Th = 1.0)$ criteria in the hybrid schemes. Finally, a trivial difference between the 95-105 km/h and 80-140 km/h speed scenarios is noticed for all investigated schemes.

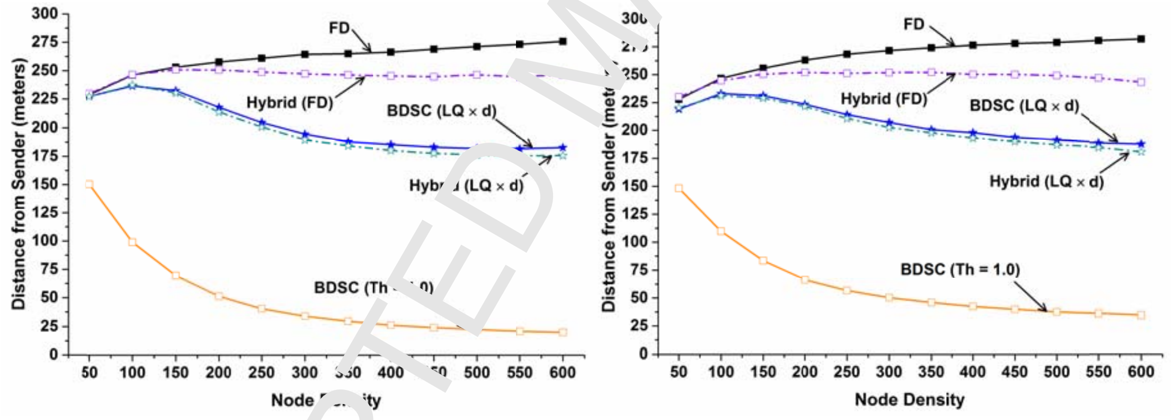


Figure 7: Spatial distribution obtained by the hybrid schemes as a function of node density and with mobility speed ranges (a) 95-105 km/h (b) 80-140 km/h.

The link quality ratios of the investigated schemes along with their spatial distributions have direct impact on the hop counts required by the schemes for delivering a message to the destination. In this research, the hop counts is estimated for end-to-end communication scenarios. As far as it is concerned with the proposed Hybrid (FD) and Hybrid $(LQ \times d)$ schemes, a small hop counts increment is observed when compared to their counterpart conventional schemes, presented by Figure 8 (a) and (b) for the 95-105 km/h and 80-140 km/h speed scenarios, respectively. This in-fact is just a reflection of the spatial distribution behavior of the two proposed variants in the hybrid scheme, where relay nodes selected based on Hybrid (FD) and Hybrid $(LQ \times d)$ fall slightly closer to the sender as compared to FD and BDSC $(LQ \times d)$, respectively, leading towards small increment in the required hop counts. In addition to hybrid scheme attributes, Figure 8 also presents the hop counts required by the investigated conventional schemes.

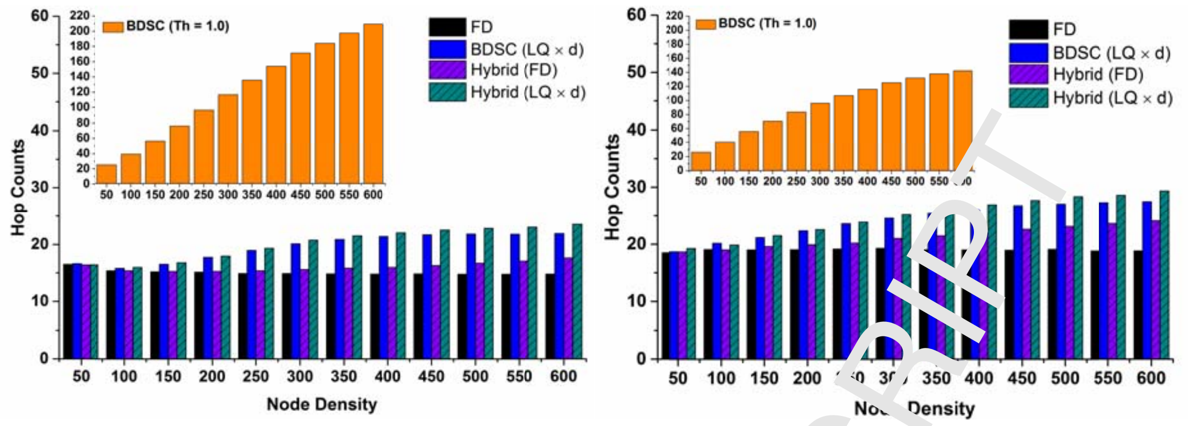


Figure 8: Hop counts obtained by the hybrid schemes as a function of node density and with mobility speed ranges (a) 95-105 km/h (b) 80-140 km/h.

While focusing on the highest considered node density of 600 nodes VANET, the relaying contribution exhibited by the hybrid scheme is presented in Tables 4 and 5 for the 95-105 km/h and 80-140 km/h speed scenarios, respectively. The values in Tables 4 and 5 focus on the relaying contribution for relays having the "relay priority indexes" $i = 0\ to\ 2$, since most of the relaying is performed by these nodes. Over the 80-140 km/h speed scenario, a fall in relaying contribution is exhibited by those relays having the "relay priority indexes" $i = 0$ for the Hybrid (FD) and the conventional FD schemes, when compared to their counterparts in the 95-105 km/h scenario. This actually results in higher contribution by relays with "relay priority indexes" $i = 1$ and 2, hence increasing the "relay waiting time" and hence the overall end-to-end delay. In contrast, the Hybrid $(LQ \times d)$ and the conventional BDSC $(LQ \times d)$ schemes tend to maintain the relaying contributions performed by the relays with "relay priority indexes" $i = 0$ when evaluated over both considered speed scenarios, hence low end-to-end delay is expected to be obtained over both underlying scenarios.

Table 4: Relaying contribution of nodes in (%) based on the investigated message dissemination schemes for a 600 node density VANET and over 95-105 km/h speed scenario.

	Relay Priority Index				
	0	***1***	***2***	***0-1***	***0-2***
Hybrid (FD)	75.15	9.25	4.58	84.4	88.98
Hybrid (LQ × d)	86.62	4.40	3.58	91.02	94.6
FD	83.45	9.66	2.02	93.11	95.13
BDSC (LQ × d)	89.76	5.44	1.61	95.20	96.80
BDSC (Th = 1.0)	88.28	9.53	1.60	97.82	99.41

Table 5: Relaying contribution of nodes in (%) based on the investigated message dissemination schemes for a 600 node density VANET and over 80-140 km/h speed scenario.

	Relay Priority Index				
	0	***1***	***2***	***0-1***	***0-2***
Hybrid (FD)	62.73	14.99	4.66	77.72	82.38
Hybrid (LQ × d)	86.74	4.73	3.08	91.47	94.55
FD	65.82	16.37	6.16	82.19	88.35
BDSC (LQ × d)	88.95	5.62	1.62	94.58	96.20
BDSC (Th = 1.0)	83.37	12.13	3.01	95.50	98.51

7. Performance Evaluation

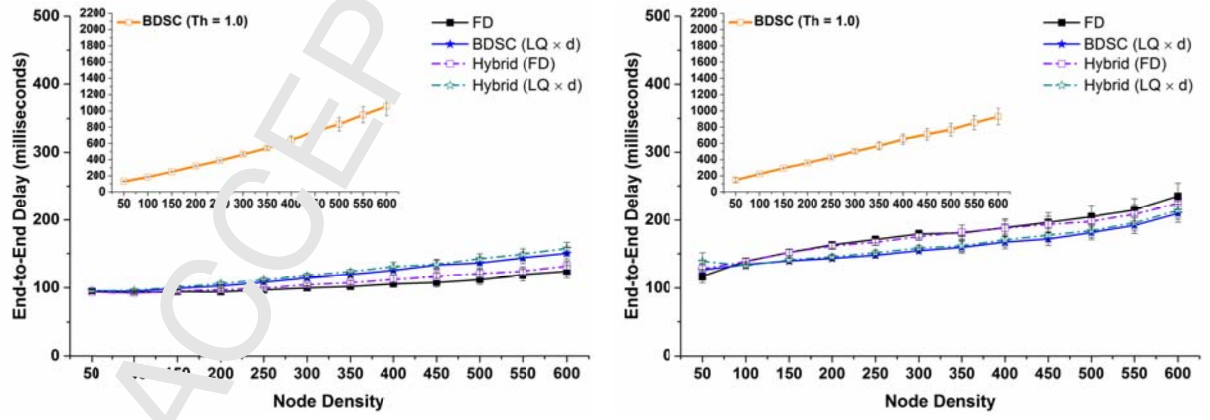
This section presents and discusses the performance results of the two proposed variants in the hybrid scheme, with investigation focus on three performance measurement metrics, i.e. end-to-end delays, reachability and saved rebroadcasts. The end-to-end delay is an important performance metric when evaluating message dissemination schemes in VANETs [16, 17, 32]. The end-to-end delay is measured between two ends in a platoon of vehicles, as the total time required for the message that was initiated by the leading node of the platoon to reach the last node of the same platoon [16, 17]. The delay between two consecutive relays is usually influenced by four delay factors, including the processing delay, transmission delay, channel access delay and propagation delay. For the case of *sender-oriented* relay selection mechanism, another delay factor is added at each relaying node which is the "relay waiting time" of each contending relay. Reachability represents the percentage of nodes that received the message out of the total nodes that are reachable either directly or indirectly [32]. Direct reachability indicates a single-hop communication, whereas an indirect reachability indicates a multi-hop communication scenario. In this work, reachability is measured for both conditions in which the broadcasted messages have reached and have not reach the last node in the platoon. The saved rebroadcast depicts the amount of bandwidth being saved while disseminating a message over a targeted coverage area, where higher saved rebroadcast indicates better bandwidth utilization by the underlying broadcast mechanism. The saved rebroadcast determines the number of rebroadcasts saved while relaying the received messages [32], as present by $(r-u)/r$, in which r represents the total number of nodes that received the message and u is the total number of nodes that rebroadcasted the received message.

We consider a confidence interval of 95% for the mentioned performance measurement metrics. Each result point is obtained by averaging over 40 simulation runs, where the result of each run is averaged over the broadcast of 600 application messages. Hence, each result point presented in this section is as a result of averaging over the broadcast of 24,000 application messages.

8.1 End-to-End Delay

Figures 9 and 10 show the end-to-end delay performance obtained by the hybrid schemes for simulation scenarios of 2 *HELLO* packets/sec and 10 *HELLO* packets/sec, respectively. In the adopted traffic load conditions, higher end-to-end delays are generally observed in the 10 packets/sec traffic load scenario as compared to its counterparts in the 2 packets/sec scenario.

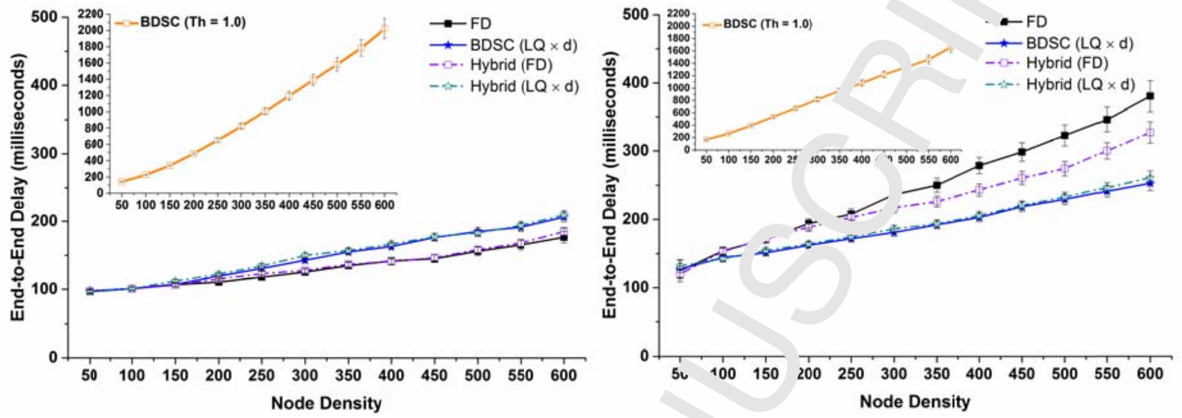
For the traffic load scenario of 2 *HELLO* packets/sec, Figure 9 (a) presents the end-to-end delay over the 95-105 km/h speed scenario in which it exhibits a marginal increments in delay by the proposed Hybrid (FD) and Hybrid $(LQ \times d)$ schemes over the conventional FD and BDSC $(LQ \times d)$ schemes, respectively. The delay increment exhibited by the two variants in the hybrid schemes is mainly a reflection of the increment in their respective hop counts, as discussed earlier in Section 6. On the other hand, Figure 9 (b) presents the end-to-end delay over the 80-140 km/h speed scenario in which the end-to-end delay tends to increase noticeably for the conventional FD scheme. This is due to being more influenced by the delay induced through the "relay waiting time" as compared to that by the hop count, discussed earlier in Section 4.1.4. In-fact, the Hybrid (FD) scheme exhibits a lower end-to-end delay compared to the conventional FD scheme. This is due to being influenced by BDSC $(LQ \times d)$ as a building block within the Hybrid (FD) scheme that results into having a lower "relay waiting time" than the conventional FD scheme. In-fact, the end-to-end delays of the Hybrid (FD) scheme lies approximately between the delays exhibited by the conventional FD and BDSC $(LQ \times d)$ schemes as a result of being simultaneously influenced by both schemes' end-to-end delay behavior.



(a) (b)

Figure 9: End-to-end delay performance for the hybrid schemes with 2 *HELLO* packets/sec and mobility speed of (a) 95-105 km/h (b) 80-140 km/h.

For the traffic load scenario of 10 *HELLO* packets/sec, Figure 10 presents similar performance patterns to those obtained in the 2 *HELLO* packets/sec scenario. However, a more prominent increase in the end-to-end delay in the conventional FD scheme is observed as the communication environment becomes more stringent. This is the case observed for the adopted high traffic load scenario when evaluated over a mobility speed profile varying between 80-140 km/h, as presented by Figure 10 (b). In contrast, the Hybrid ($LQ \times d$) and BDSC ($LQ \times d$) schemes tend to maintain the lowest and almost similar end-to-end delays as the communication environment becomes more stringent.



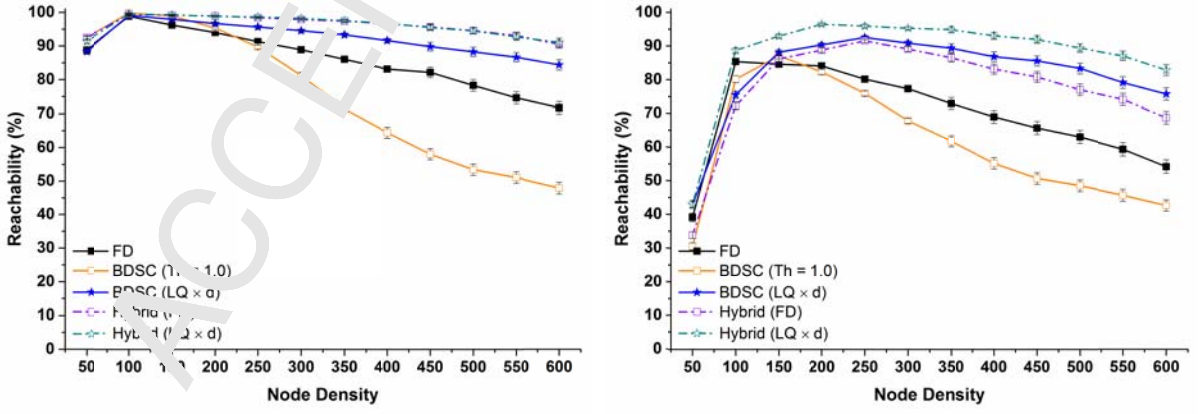
(a) **(b)**

Figure 10: End-to-end delay performance for the hybrid schemes with 10 *HELLO* packets/sec and mobility speed of (a) 95-105 km/h (b) 80-140 km/h.

8.2 Reachability

Figures 11 and 12 show the reachability performance obtained by the hybrid schemes for simulation scenarios of 2 *HELLO* packets/sec and 10 *HELLO* packets/sec, respectively. In the adopted traffic load conditions, lower reachability is generally observed in 10 packets/sec traffic load scenario as compared to its counterparts in 2 packets/sec scenarios.

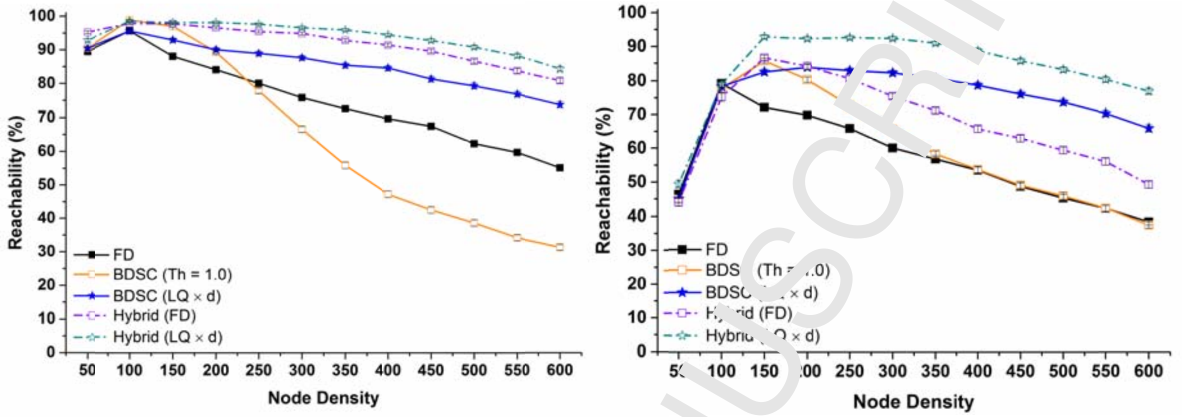
For the traffic load scenario of 2 *HELLO* packets/sec, a reachability improvement is shown by both hybrid schemes over high node density networks when compared against the conventional schemes, as presented by Figures 11 (a) for the 95-105 km/h speed scenario. On the other hand, the Hybrid (FD) scheme generally falls below in performance when compared to the conventional BDSC ($LQ \times d$), as presented by Figure 11 (b) for the 80-140 km/h speed scenario. The poor performance of Hybrid (FD) over the 80-140 km/h is influenced by FD being the first relay selection criterion in ordered-combination of the hybrid scheme. However, in the same 80-140 km/h mobility scenario, the Hybrid ($LQ \times d$) scheme outperforms all conventional schemes and over all considered node densities. Hence, in can be stated that the Hybrid ($LQ \times d$) scheme exhibits reachability improvements against the conventional FD and BDSC ($LQ \times d$) schemes.



(a) **(b)**

Figure 11: Reachability performance for the hybrid schemes with 2 *HELLO* packets/sec and mobility speed of (a) 95-105 km/h (b) 80-140 km/h.

For the traffic load scenario of 10 *HELLO* packets/sec, Figure 12 presents similar performance patterns to those exhibited in the 2 *HELLO* packets/sec scenario. However, a more prominent performance gain is noticed by the hybrid scheme, especially the Hybrid $(LQ \times d)$ when compared to the conventional FD and BDSC $(LQ \times d)$ schemes. In-fact, a steeper fall in reachability performance is observed for the conventional FD scheme as the communication environment becomes more stringent. While more robust performance is observed by the Hybrid $(LQ \times d)$ scheme over more stringent communication conditions.

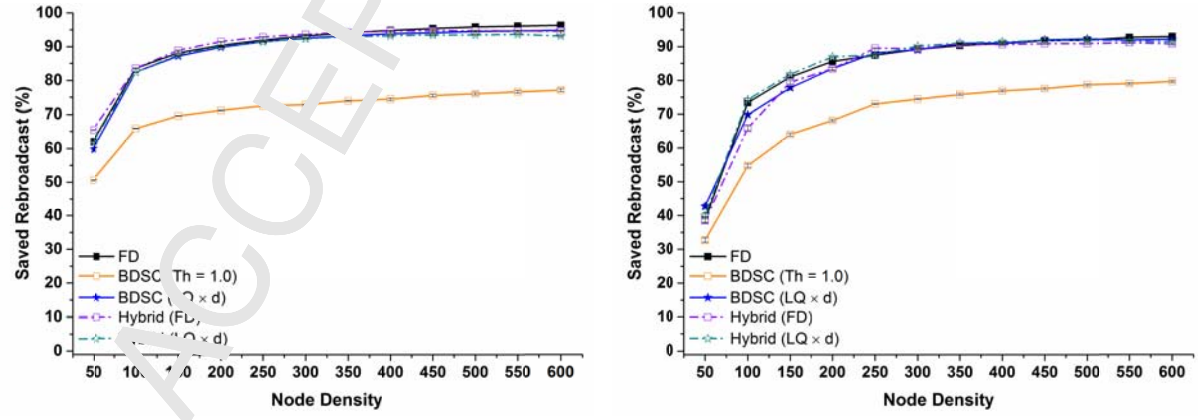


(a) (b)

Figure 12: Reachability performance for the hybrid schemes with 10 *HELLO* packets/sec and mobility speed of (a) 95-105 km/h (b) 80-140 km/h.

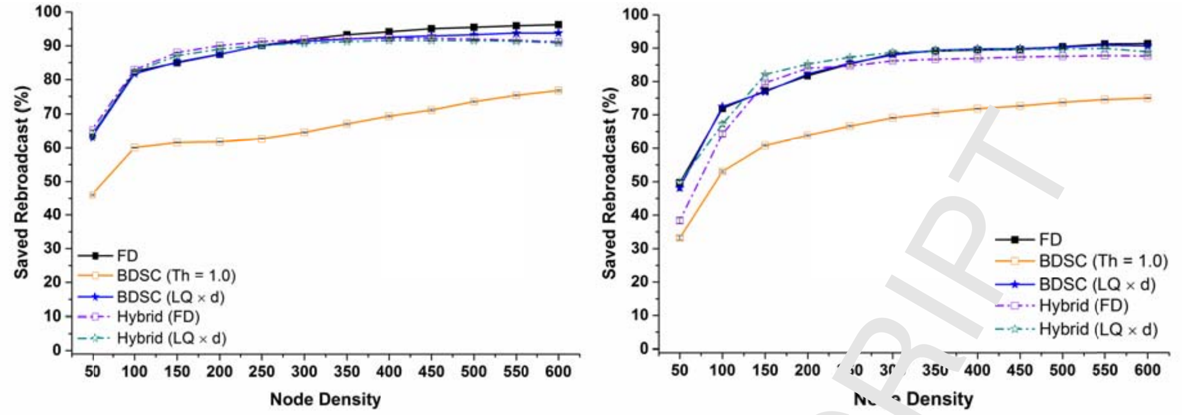
8.3 Saved Rebroadcast

Bandwidth utilization of the proposed hybrid scheme is evaluated in terms of saved rebroadcast, and is presented by Figures 13 and 14 for the 2 *HELLO* packets/sec and 10 *HELLO* packets/sec traffic load scenarios, respectively. In high node density networks, both variants in the hybrid scheme exhibit good performance levels in terms of saved rebroadcast over both considered traffic load scenarios and over both speed scenarios as well. In-fact, minor impact on saved rebroadcast performance can be observed out of the change in traffic load conditions. The saved rebroadcasts of both hybrid scheme fall marginally short of that obtained by the conventional FD and BDSC $(LQ \times d)$ schemes, while surpassing the BDSC $(Th = 1.0)$, over all considered scenarios. When comparing Hybrid (FD) with Hybrid $(LQ \times d)$, almost similar performance is exhibited by the schemes over high node density networks. In contrast the proposed hybrid and the conventional FD and BDSC $(LQ \times d)$ schemes, the conventional BDSC $(Th = 1.0)$ exhibits poor saved rebroadcast ratio due to the large number of hop counts required to deliver a message to a certain node in the network.



(a) (b)

Figure 13: Saved rebroadcast performance for the hybrid schemes with 2 *HELLO* packets/sec and mobility speed of (a) 95-105 km/h (b) 80-140 km/h.



(a) (b)

Figure 14: Saved rebroadcast performance for the hybrid schemes with 10 *HELLO* packets/sec and mobility speed of (a) 95-105 km/h (b) 80-140 km/h.

8. Conclusions

This paper has introduced the concept of hybrid relay nodes selection along with two variants within the hybrid scheme, referred to as the Hybrid (FD) and Hybrid ($LQ \times d$), for efficient multi-hop message dissemination in VANETs. By adopting the *sender-oriented* relay nodes selection mechanism, the hybrid scheme selects a group of relay nodes while using an ordered-combination of different relay selection criteria. This is in contrast to the conventional schemes where a group of relay nodes is selected by means of a single message dissemination scheme. Performance of the hybrid scheme has been evaluated over two varying traffic load conditions with periodic packets frequency of 2 *HELLO* packets/sec and 10 *HELLO* packets/sec. For each traffic load condition, two different mobility speed scenarios are considered ranging from 95-105 km/h and 80-140 km/h. In the most stringent communication scenario considered in this work, i.e. traffic load of 10 *HELLO* packets/sec, mobility speed between 80-140 km/h and node density of 600 nodes, a reachability improvement up to 10% and 40% is exhibited by the Hybrid ($LQ \times d$) over the conventional BDSC ($LQ \times d$) and FD schemes, respectively. These improvements are obtained in most cases without scanting the end-to-end delays or saved rebroadcasts. In light of the obtained results, we affirm that adopting a single criterion for relay nodes selection limits the reachability performance, whereas adopting multiple criteria for the same improves that performance. The proposed Hybrid ($LQ \times d$) scheme displayed more robustness to adverse communication conditions as compared to all other conventional schemes, especially as the node density and traffic load increases. Robustness of Hybrid ($LQ \times d$) was clearly observed through its sustainability in reachability performance. The Hybrid ($LQ \times d$) has shown the best reachability performance over a traffic load conditions of 2 *HELLO* packets/sec when evaluated over both considered mobility speed scenarios of 95-105 km/h and 80-140 km/h. In-fact, similar performance patterns were observed for Hybrid ($LQ \times d$) over the same mobility scenarios while increasing the traffic load condition from 2 *HELLO* packets/sec to 10 *HELLO* packets/sec.

The hybrid relay nodes selection scheme can be further improved by studying and devising other potential combinations between the different relay selection criteria. Another interesting future direction for this research work could assess the performance of the proposed hybrid scheme using more realistic simulation environments, such as adopting actual road maps models for urban/rural environments, more realistic mobility patters (such as by using SUMO, VISSIM), and wireless propagation channels which take into account both channel fading and radio obstacle effects. An interesting area to explore would be the optimization of relay nodes selection in VANETs through the development of a decentralized random walk based algorithm, which could further improve communication efficient over complex communication scenarios. Since these algorithms are graph-based, hence it is possible to use a graph to describe the nodes and their selection over a VANET.

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Highlights

- A new class of hybrid relay nodes selection scheme is proposed for VANETs.
- The hybrid scheme attempts to exploit the best features of existing schemes.
- Hybrid scheme improves reachability especially over a highly dense VANETs.
- Reachability is improved without scanting end-to-end delays or saved rebroadcasts.