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Robust Backbone Network Based on Hybrid Selection of Relays for Multi-hop Data Dissemination in VANETs

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Abstract

Relay nodes selection as a key word to ensure efficient multi-hop data dissemination in VANETs has received tremendous attention for many years. However, previous literatures usually lack to address two important topics, namely how to intelligently distribute the relay nodes inside the area of interest to ensure the information coverage; and how to simultaneously exploit the best features of both existing sender-oriented and receiver-oriented relay selection mechanisms in one hybrid scheme to avoid the trade-off among them and improve the overall dissemination efficiency. In this paper, we tackle the aforementioned topics by proposing a Robust BACKbone NETwork based on Hybrid Selection of Relays for multi-hop data dissemination in VANETs (BACKNET-HSR). First, we define one new message propagation pattern as the guidance of the relay selection and inhibition rules. It mainly aims to avoid the chaotic distribution of relays by realizing a synergy among the potential relay candidates to build an on-the-fly backbone network parallel to the road lines topology in a distributed manner. In order to enhance the relay selection robustness, we propose a tight coupling of both investigated relay selection mechanisms in one hybrid algorithm that attempts to simultaneously exploit the low latency of sender-oriented approaches and the high network reachability of receiver-oriented approaches. Simulation results show that the proposed scheme disseminates data with low delay and high information coverage, outperforming the existing dissemination protocols in different scenarios and under varying vehicular densities.

Keywords: Vehicular networks, VANETs, Data dissemination, Backbone, Relay nodes, Multi-hop

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1. Introduction

The ever-growing number of vehicles combined with the unprecedented technological progress pose a serious interest from researchers and recent automotive markets in the emerging Vehicular Ad-hoc NETWORKS (VANETs). VANETs open up the possibility of the connected car concept through enabling a Vehicle-to-Everything (V2X) communication paradigm, which can boost the development of numerous Intelligent Transportation Systems (ITS)-based applications ranging from entertainment to safety-related, including navigation and infotainment services [1, 2]. Realizing cooperative communications between vehicles without the need of the coordinator entities, e.g., Road Side Unit (RSU), is among the primary motivations of VANETs since they help to reduce the economical cost of the connected cars implementation, as well as avoiding some intrinsic problems brought by the use of a centralized network manager, such as the channel competition and packets congestion problems. To achieve this goal, each vehicle in VANETs is assumed to be equipped with a Dedicated Short-Range Communication (DSRC) [3] device, making it able to directly exchange information with its nearby neighbors, e.g., the exchange of Basic Safety Message (BSM) [4] or Cooperative Awareness Message (CAM) [5].

In VANETs, some information are recognized as data for the public interest, where their real-time delivery could significantly enhance the traveling experience [6, 7], and especially boost the road safety applications by extending the knowledge bases of vehicles with numerous up-to-date information about various road conditions. The main challenge in this field arises from the fact that the sent data should be disseminated in a wide Area-of-Interest (AoI), while the sending vehicles are equipped with the limited DSRC devices. In order to handle this challenge, one promising technique is to allow messages to be spread over multiple depots in an ad hoc manner through a Vehicle-to-Vehicle (V2V) communication. However, Considering some intrinsic Inter-Vehicular Communication (IVC) [3] characteristics, it is obvious that the multi-hop retransmission paradigm is not mature enough to provide reliable dissemination process in VANETs. Indeed, due to the shared data load, vehicular traffic density, the lack of a coordinator entity to manage the channel allocation and contention, and the limited radio medium dedicated for VANETs [1], serious broadcast storm and packet collisions threaten the availability and timeliness of the network. Reducing the communication burden by enabling only a subset of vehicles to relay the sent messages (referred

30 to as relay nodes) has long been debated to be efficient solution for reducing data redundancy
31 and wireless channel damage [8, 9, 10, 11, 12]. Nevertheless, it still hard to design a robust relay
32 selection technique that can handle the characteristics of VANETs in a fully distributed manner
33 [2]. For instance, the high-speed of vehicles induces a fast-changing network topology and frequent
34 disconnection of the wireless communication links, resulting in a poor network reachability. This
35 will lead to a serious packet loss problem and becomes more severe when increasing the network
36 complexity. For example, the physical obstacles in the complex urban scenarios can easily intersect
37 the transmitted signal and block the end-to-end communications [13].

38 Designing a robust relay selection algorithm is a unique problem for disseminating messages in
39 VANETs, a poor selection of relays can easily lead to a poor reachability and message coverage
40 capability, high latency, and even to the reproduction of the broadcast storm [14]. In general,
41 existing relevant works address the issues of data dissemination in VANETs in two different ways
42 [15]. Some exploit the one-hop neighbors information gathered by means of the beacon messages
43 to explicitly select the relay nodes at the sender side, referred to as sender-oriented relay selection
44 mechanism; and others aim to improve the network reachability and avoid the beacon exchanging
45 cost by adopting an implicit selection of relays, referred to as receiver-oriented relay selection
46 mechanism. Each mechanism has its unique benefits and shortcomings, thus its own problems
47 that are driving the research aspects. For example, sender-oriented schemes can achieve a rapid
48 propagation of messages, but they are very sensitive to the mobility of vehicles. On the other
49 hand, receiver-oriented schemes exhibit high tolerance with the high speed of vehicles, but with an
50 extra transmission delay. Besides, regardless of whether the relay selection is sender-oriented or
51 receiver-oriented, it should be noted that the geometric distribution of relays almost determines the
52 message coverage efficiency. The selected relays should be adequately distributed inside the targeted
53 dissemination area to ensure an optimal coverage of the entire AoI. Nevertheless, we observed
54 that this requirement have not been effectively addressed in most of the existing dissemination
55 protocols, incurring the chaotic distribution of relays and resulting in a poor information coverage.
56 Instead of the flat network structure, creating a network hierarchy in VANETs can bring significant
57 advantage for the data delivery by managing the message retransmissions process in a structured
58 manner. Meanwhile, there are other challenges over a dynamic VANET topology, especially, the
59 maintenance and creation of stable network structure with less overheads [16].

60 In light of the above description, this paper is proposed with the aim to construct a Robust

61 BACKbone NETwork based on Hybrid Selection of Relays for multi-hop data dissemination in
62 VANET, namely as BACKNET-HSR. Robustness is achieved by simultaneously addressing the most
63 intrinsic data dissemination challenges stemming from the unique characteristics of VANETs, such
64 as the unexpected packets loss, frequent failures of the communication links, expanded latency and
65 the distributed nature of VANETs. First, one new relays distribution model is envisaged to avoid
66 the chaotic distribution and ensure the information coverage capability. Then, we comprehensively
67 adjust the relays selection and inhibition rules to realize the envisioned relays distribution in a
68 distributed manner. Moreover, we tend to ensure reachability and reduce the latency by realizing a
69 tight coupling of both existing sender-oriented and receiver-oriented relay selection mechanisms in
70 one hybrid scheme. In more detail, the main contributions presented by this paper are summarized
71 as follows:

- 72 • This paper gives out a deep overview of sender-oriented and receiver-oriented relay selection
73 mechanisms, as well as a qualitative comparison among them.
- 74 • This paper identifies the causes behind the chaotic distribution of relays in previous dissemi-
75 nation works. To solve this problem, we envisaged one new relay distribution model based on
76 the road map topology. In order to achieve the envisioned relay distribution model in a dis-
77 tributed VANET structure, we design one new message propagation pattern as the guidance
78 of the relays selection and inhibition rules. As soon as the dissemination process is triggered,
79 a synergy between the potential relay candidates is realized to build an on-the-fly backbone
80 structure parallel to the road lines.
- 81 • This paper aims to enhance the relay selection robustness by exploiting the best features of
82 the aforementioned relay selection mechanisms. An explicit selection of relays is performed
83 at the senders side to provide a continuous retransmission at the application layer while com-
84 prehensively taking into account the mobility of vehicles, the communication links conditions
85 and the static physical obstacles in the urban scenarios. As important disconnection of the
86 communication links could be occurred unexpectedly, we use a contention-based relay selec-
87 tion technique to monitor the propagation of the sent message and compensate for the lost
88 packets by implicitly selecting alternative relays upon capturing one failed communication be-
89 tween the explicitly selected relays. Different timer settings are defined to ensure the ordered
90 combination of both adopted relays selection mechanisms.

- 91 • Experiment simulations are carried-out under varying vehicular traffic densities and different
92 scenarios to assess our proposed scheme with some other existing protocols, revealing that our
93 proposed scheme efficiently improves the message coverage capability and noticeably reduces
94 the transmission delay.

95 The remainder of this paper is organized as follows: Section 2 discusses the existing work on
96 data dissemination in VANETs. Section 3 gives a detailed description of the problems encountered
97 in this field. Section 4 gives the main components of the proposed scheme. Section 5 presents the
98 proposed scheme in detail. The simulation results are analyzed in section 6. Finally, the last section
99 provides a brief overview of our future work and concludes this work.

100 2. Related work

101 Multi-hop data dissemination is among the main research topics of VANETs in previous lit-
102 eratures [2]. Flooding has long been exhibited as the simplest way of disseminating data over
103 the mobile ad hoc networks, each vehicle roaming inside the AoI broadcasts every incoming mes-
104 sage once. Although the blind flooding has high performance efficiency under the sparse network
105 scenarios, it disrupts the network availability by generating the broadcast storm problem when
106 increasing the network density. Hence, it easily lead to a serious network congestion and packet
107 collisions [14, 16]. In order to mitigate these problems, previous relevant works tend to adopt such
108 a broadcast suppression technique [16] to avoid the unnecessary retransmissions. Only a subset of
109 potential vehicles will be allowed to relay the disseminated data, while the others will be inhibited.
110 At this point, it should be noted that a poor selection of the relay nodes will undoubtedly under-
111 mine the dissemination efficiency in many regards, such as latency, overheads, and particularly the
112 message coverage capability [14]. As described earlier, based on either the relay selection process
113 is performed by the sender or the receiver nodes, existing broadcast suppression techniques can be
114 classified into two main classes: sender-oriented and receiver-oriented relay selection mechanisms.
115 Next, we will detail these two major techniques, and then we give a qualitative comparison study
116 between them listed in Table 1.

117 2.1. Sender-oriented relay selection mechanism

118 This class can be referred to as beacon-assisted relay selection mechanism. It exploits the one-
119 hop neighbors information gathered by means of the exchanged beacon messages to explicitly select

Table 1: Comparative study of sender-oriented and receiver-oriented relays selection mechanisms

Features	Sender-oriented mechanism	Receiver-oriented mechanism
Relays selection rule	Explicit selection of relays – Before each broadcast, the sender vehicle should select the next hop relays and incorporate their identifiers inside the disseminated message.	Implicit selection of relays – Upon receiving the message, the vehicle should hold it and schedule a back-off timer. The vehicle relay the message once the initiated timer expires.
Inhibition rule	Only the receivers finding their identifiers incorporated inside the sent message are allowed to broadcast, the other are inhibited.	Each node that hear retransmission of an already scheduled message must immediately cancel its transmission.
Advantages	Enables a continuous retransmission paradigm at the application layer, which can promote the development of the delay-sensitive applications. Provides a good scalability when designing the relay selection rules [14].	Exhibits good tolerance with the frequent disconnection of the communications links between mobile vehicles. No prior information are required to perform the dissemination process (beaconless solution).
Drawbacks	Exhibits high sensitivity to the frequent disconnection of the communication links in VANETs. Requires up-to-date information about the one-hop network condition (beacon-assisted solution).	Adopts an intermittent retransmission paradigm that noticeably increase the latency. Not recommended for the delay-sensitive applications.
Frequent addressed issues	Handling the broadcast storm problem. Maintaining stable communication links by considering several conditions, such as link connectivity [16], link life time [17], successful transmission probability [18], and the use of an obstacle avoidance forwarding strategy [13]. Enhancing the information coverage capability by adopting several techniques, such as the construction of an hierarchical network topology [16, 19], and the assignment of the highest rebroadcast priority to the relay candidates that have dense local networks [20]. Handling the unexpected link disconnection problem by selecting auxiliary relay(s) [21, 14, 12].	Handling the broadcast storm problem. Handling the expanded latency through the use of a probabilistic-based solution [22, 23, 10, 24], or the reduction of the contention timer [9, 25, 26, 27]. Avoiding packet collisions by preventing the simultaneous retransmissions problem for both probabilistic-based solutions [28, 10, 24], and timer-based solutions [29, 30, 31]. Enhancing the information coverage capability by designing a relays distribution model for the timer-based solutions, as in [11], or assigning priority to the relay candidates with high local densities for the probabilistic solutions, as in [10].

120 the next-hop relays at the sender side. The current relay node should elect among its vicinity
121 one or more neighbors to become the next dissemination entities, incorporates their identifiers
122 inside the message and broadcast it. When receiving the sent message, each receiver first needs
123 to judge whether or not it has been explicitly selected to become a relay node by checking the
124 content message relay list. If yes, it will forward the message; else, it will be inhibited. As this
125 type of mechanism provides the possibility of a continuous retransmissions at the application layer,
126 sender-oriented solutions achieve promising performance in network latency, which can promote
127 the development of the delay-sensitive applications [14]. However, they exhibit high sensitivity
128 to the frequent disconnection of the communication links in VANETs. In fact, considering the
129 high mobility of vehicles, the presence of physical obstacles, the channel fading operation, the
130 hidden nodes problem, etc. there is no guarantee that the explicitly selected relays (i.e., the only
131 ones enabled to broadcast) will correctly receive the sent message. Hence, a serious packet loss is
132 possible in this case.

133 In general, most of the existing dissemination solutions in VANETs exploit the furthest distance
134 approach to reduce both data redundancy and end-to-end delay. The neighbor farther away from the
135 sender is recognized as the ideal next-hop relay. Besides, sender-oriented solutions emphasized on
136 the availability of the explicitly selected relays to avoid packets loss. To this end, several techniques
137 have been proposed to enhance reachability between the neighboring relays [13, 16, 18, 12, 17].
138 A link stability measurement based on the regularity of the incoming beacons has been proposed
139 in [12]. It assigns priority to the neighbors with stable forwarding links to become the next-hop
140 relays. The combination of multiple link quality parameters to mitigate the unexpected link failure
141 problem has been widely studied in this regard [16, 17]. The link state can be determined based
142 on several conditions, such as link connectivity [16], link life time [17] and successful transmission
143 probability [18]. By increasing the dissemination constraints, other solutions tend to achieve robust
144 relay selection process under complex VANET scenarios. Some are proposed with the aim to prevent
145 intersecting the physical obstacles when establishing communications between neighboring relays,
146 reducing the channel fading effect by enabling an obstacle avoidance forwarding strategy [13]; and
147 others consider the security constraints when selecting the relay nodes [32].

148 The improvement of information coverage is also within interests of existing literature. The
149 goal is to enhance the message coverage capability by maximizing the number of vehicles receiving
150 the message. To this end, the work in [20] takes into account the local density of each vehicle

151 during the relays selection process, the neighbor with high local density and falls farther away
152 from the sender is more likely to become the next-hop relay. Other works achieve better coverage
153 performance by allowing a multiple selection of the next-hop relays [21, 14, 12]. A path diversity
154 broadcast solution is proposed in [21]. Instead of selecting only one relay, an auxiliary relay is
155 selected to reinforce the message delivery capability. In order to reduce redundancy, the auxiliary
156 relay will only broadcast the sent message without performing the relay selection process. A Bi-
157 directional Stable Communication (BDSC) scheme [12] is proposed to improve both reachability
158 and coverage. The main idea behind BDSC is to let every vehicle select 12 potential neighbors as
159 relay candidates, ordered in a relay priority list based on the Link Quality (LQ) influence factor.
160 simultaneous retransmission is effectively addressed by using a contention-based retransmission
161 paradigm. Data redundancy is also addressed by forcing the explicitly selected relays to cancel
162 their scheduled transmissions upon hearing a twice copies of the same message. Two variants of
163 the BDSC scheme have been proposed in [14]. The main idea behind these variants is to combine
164 multiple selection metrics when constructing the relay priority list, such as the furthest distance
165 approach and the bi-directional link stability influence factor. Thus, achieving better performance
166 than the original BDSC scheme under different traffic load conditions, particularly in terms of
167 the end-to-end delay and the generated overheads. Hierarchical networks are also exhibited as
168 promised techniques for improving the message coverage capability by overcoming the limitations
169 of the flat network structure in VANETs. Within the context of data dissemination, we recognize
170 the clustering approaches as representative solutions for attempting such a network hierarchy, like
171 in [16, 19]. Vehicles are organized into multiple connected clusters, and each cluster is managed by
172 a controller entity named cluster-head. During the dissemination process, messages will be routed
173 toward the cluster-heads, then forwarded towards the cluster-members in an hierarchical manner.
174 The main drawback of these solutions is that the formed hierarchy should be stable to ensure
175 the structured propagation of the sent messages, which is hard to be realized in a time-varying
176 VANET topology. Thus, any topology change should be reported to all relevant nodes, incurring
177 an important communication overhead.

178 *2.2. Receiver-oriented relay selection mechanism*

179 While sender-oriented solutions faced the most intrinsic VANET challenge (i.e., the severe packet
180 loss stemming from the frequent disconnection of the communication links), other research studies

181 were proposed with the aim to fully overcome this issue by using a receiver-oriented relay selection
182 mechanism. The main idea behind the latter mechanism is to make each receiver vehicle able to
183 make its own broadcast decision in a distributed manner without the need of any prior knowledge
184 about the surrounding network conditions, e.g., the neighbor location, the already established link
185 connections, etc. For this reason, receiver-oriented solutions are known as beaconless approaches,
186 where their main advantage is usually referred to dispensing the beacon exchanging load [30, 25].
187 Although this benefit is true in the dissemination context, it should be noted that beacon messages
188 have been standardized by the European Telecommunications Standards Institute (ETSI) as a
189 cornerstone of the cooperative awareness service [5], particularly for the safety-related services. In
190 reality, The main purpose of the receiver-oriented mechanism is to fit the fast-changing VANET
191 topology by avoiding the link conditions dependency when designing the relays selection rules.
192 Upon receiving the sent message, the vehicle decides whether or not it becomes a relay node based
193 on some predefined rules which can be probabilistic-based or timer-based. Probabilistic solutions
194 [22, 23, 10] allow vehicles to forward the received message with a calculated probability that is
195 usually associated with the distance and redundancy parameters. Like the sender-oriented solutions,
196 probabilistic techniques can provide a continuous retransmission at the application layer, resulting
197 in low dissemination latency. However, they lead to severe packet collisions and channel damage due
198 to the simultaneous rebroadcasts from nearby nodes (multiple neighbors can have high broadcast
199 probability of the same message, especially in dense VANET scenarios). Timer-based approaches
200 [11, 9, 25, 30] have been exhibited as promising alternative of the probabilistic approaches, since
201 they effectively address the issue of the simultaneous rebroadcasts through the use of contention.
202 For every incoming message, the vehicle holds it and schedules a transmission timer that is usually
203 computed based on the distance between the couple sender-receiver vehicles. If the initiated timer
204 expires, the vehicle becomes a relay node and broadcasts the message. Data redundancy has been
205 effectively mitigated by forcing vehicles to immediately canceling their scheduled transmissions
206 upon hearing new transmission of the same scheduled message (inhibition rule). Among the main
207 drawbacks of timer-based solutions, we can cite the use of a back-off timer at the application layer,
208 which leads to an intermittent retransmission paradigm and noticeably expands the dissemination
209 delay, particularly as we exploit the multi-hop retransmission technique over a large scale VANET
210 network.

211 The work in [28] addresses the simultaneous retransmissions problem of p-Persistence [8] scheme

212 through combining the furthest distance algorithm with the mobility of vehicles. It assigns the
213 highest rebroadcast priority to the receivers far away from the sender and have similar movement
214 direction, which could reduce the number of contending vehicles. The applicability of a probabilistic
215 technique to different vehicle densities has been also studied in [10], revealing that adjusting the
216 forwarding probability with the local density of vehicles could enhance the coverage capability with
217 less communication burden. An approach to improve the reliability of the probabilistic forwarding
218 consists of using fuzzy logic to calculate the broadcast probability of vehicles by taking into account
219 the buffer load, angular orientation, and the movement direction of each vehicle [24].

220 Timer-based solutions have gained important attention in the recent years. DRIVE [11] in-
221 troduces a sweet spot concept to maximize the message coverage capability under varying traffic
222 conditions. The communication radius of the sender vehicles is divided into four quadrants, a sweet
223 spot is defined in each quadrant as the most suited zone in which the next hop relay should be
224 located. DRIVE aims to maximize the coverage capability by allowing the farthest vehicle inside
225 each sweet spot to relay the disseminated data. However, the authors in DRIVE do not adjust their
226 proposed inhibition rule to fit the sweet spot concept, instead they adopt the indiscriminate inhi-
227 bition (discussed in Section 3), which disrupts the envisioned relays distribution model and easily
228 lead to the chaotic distribution of relays. Additionally, an extra delay is induced by the adopted
229 timer settings since there is no guarantee to find vehicles located within the sweet spots (i.e., the
230 ones with the shortest transmission-timers).

231 A Contention-Based Forwarding (CBF) algorithm [9] is proposed by the ETSI as the current
232 standard of data dissemination in VANETs. CBF can be seen as an improved version of DRIVE.
233 Instead of the sweet spot concept, CBF enables vehicles receiving one copy of the sent message to
234 become relay nodes, realizing an on-the-fly relays distribution model dynamically adjusted to fit the
235 senders' neighbors distribution. This perception enables CBF to adopt an uniform timer setting,
236 the furthest receiver from the sender is assigned with the shortest transmission timer independently
237 of the zone where it is falling inside. Although CBF achieves much better performance in network
238 latency compared to DRIVE, it still suffers from the intermittent retransmission problem since there
239 is no guarantee to find neighbors distant enough from the senders to ensure the rapid propagation
240 of messages, especially under the sparse network scenario. In contrast, in dense scenario, CBF
241 generates frequent simultaneous retransmissions since, in this particular scenario, there is a high
242 probability to find equidistant neighbor from the sender, i.e., neighbors with equal transmission

243 timers. Moreover, like DRIVE, CBF adopts the indiscriminate inhibition rule, leading to the fail
244 of the considered relays distribution model under multiples vehicular scenarios.

245 A pull-based data dissemination approach has been proposed in [25] to aggregate real-time
246 Floating Car Data (FCD). To disseminate the request messages, the authors in [25] propose a
247 reduced CBF (rCBF) to overcome the simultaneous retransmissions induced by the original CBF.
248 The main idea behind rCBF is to extend CBF's timer setting with an uniformly-distributed random
249 component, hence avoiding the simultaneous retransmissions in case of equidistant neighbors from
250 the sender, but with an extra delay. Several timer-based approaches have been proposed in the
251 literature, they are mainly focusing on the high delay issue steaming from the contention process
252 [26, 27], the collision problem that frequently occurred in case of defining short timer difference
253 among neighboring receivers [29], and the applicability of the timer-based approaches with the
254 Decentralized Congestion Control (DCC) buffer [30, 31]. In this regard, it should be noted that the
255 information coverage has not so far been effectively addressed in previous literature.

256 3. Problem description

257 Actually, the relay nodes concept has been introduced to mitigate the broadcast storm problem
258 by enabling only a subset of potential nodes to broadcast the sent messages and inhibiting the
259 others, which could significantly reduce the channel competition and packet redundancy problems.
260 Although reducing the number of relays could efficiently reduce the communication burden, it brings
261 additional challenges in terms of the network coverage, reachability and timeliness. These issues
262 are hereafter discussed as follows:

263 1) *Message coverage capability*: To the best of our knowledge, regardless of whether the adopted
264 relay selection mechanism is sender-oriented or receiver-oriented, existing dissemination schemes do
265 not consider the requirements of the geometric distribution of relays when designing the relay
266 selection and inhibition rules. This becomes more obvious when taking into account that the
267 most common inhibition rule is designed based on the information redundancy ratio, which could
268 easily lead to the the chaotic distribution of relays because of the indiscriminate inhibition of the
269 relay candidates, hence the poor information coverage. For the sake of simplicity, a representative
270 illustrations of the latter problem is shown in Fig. 1. In this figure, we consider the case of multiple
271 selection of the next hop relays [9, 11, 14, 12, 25], as they could achieve better coverage compared
272 to the other solutions. Consider that the Source Vehicle SV initiates the dissemination process

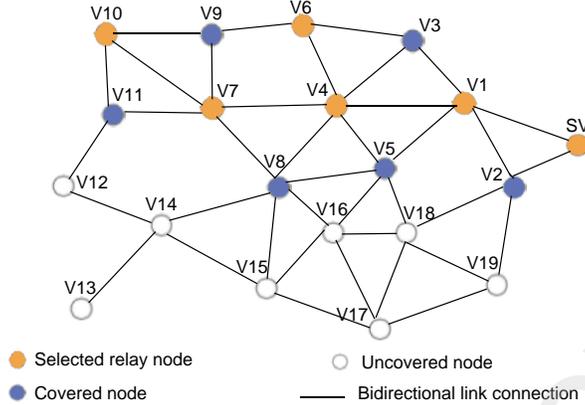


Figure 1: Effects of the indiscriminate inhibition rule on the information coverage capability

273 by broadcasting a warning message, vehicle V1 will be the first one that rebroadcasts the sent
 274 message since it has the furthest distance from SV. Assuming that vehicles V4, V7, V6 and V10
 275 are the furthest from each other, hence they will be respectively the third, fourth, fifth and sixth
 276 re-broadcaster nodes. As seen in this example, vehicles V2, V5, V8 and V11 are a very critical relay
 277 candidates since they are the only ones that could forward the sent message towards the bottom
 278 network side. However, since each one of them will receive at least twice copies of the sent message,
 279 they will be indiscriminately inhibited. Therefore, the vehicles V12-V19 will not receive the sent
 280 message even-though they are considered as belonging to the targeted AoI, which leads to the poor
 281 coverage capability. In reality, the indiscriminate inhibition problem has been overlooked in most
 282 of the existing dissemination approaches. The indiscriminate inhibition issue has been addressed in
 283 the area advanced forwarding algorithm [9], proposed by the ETSI, by increasing the redundancy
 284 tolerance ratio, vehicles receiving redundant copies of the sent message and their number still less
 285 than a given inhibition threshold will be allowed to broadcast. However, the limited DSRC channel
 286 will be overwhelmed by the unnecessary retransmissions of redundant messages. Additionally, As
 287 shown in Fig. 1, it is a challenging task to define the optimal inhibition threshold under a time-
 288 varying vehicular distribution and density.

289 2) *Network reachability and timeliness*: Because of some inherent IVC characteristics, reachabil-
 290 ity is a unique problem in VANETs, particularly for the sender-oriented schemes and even-though
 291 the link performance is taken into account when selecting the relay nodes. Receiver-oriented mech-
 292 anism could effectively avoid this problem, however, with an extra delay. Thus, a tight coupling of

293 both mechanisms in one scheme could be a promising solution to take advantage of their benefits
294 while avoiding their shortcomings. First, a sender-oriented mechanism can be adopted as the pri-
295 mary relay selection mode, hence the disseminated data could be spread rapidly. As packets can
296 be lost unexpectedly, a modified version of the receiver-oriented mechanism can be implemented
297 as a recovery strategy to capture the lost packets and implicitly select alternative relays. However,
298 this investigated coupling requires efficient inhibition rule and timer settings to ensure an ordered
299 combination of both mechanisms, as well as a robust monitoring algorithm to efficiently capture
300 the failed link connections, which is hard to achieved in a flat VANETs structure.

301 Basically, considering VANET as a flat network structure without a coordinator manager makes
302 the design of such an envisioned relay distribution model a challenging task. To handle this problem,
303 some previous works aimed to build a network hierarchy to organize the data transmission in
304 a structured manner [16, 19]. Structure-based data dissemination solution brings an important
305 improvement of the coverage capability. However, it often exhibits additional challenges for forming
306 stable network hierarchy and reducing the structure creation and maintenance overheads. In this
307 paper, we tend to take advantage of the fact that vehicles are basically distributed according to the
308 road map topology, hence a partisan vehicular distribution along with the road lines is automatically
309 formed. First, we envisaged one relay distribution model parallel to the road lines, as seen as the
310 best fit between the city settings and the characteristics of VANETs. Then, we design one new
311 message propagation pattern to realize a synergy between the relay nodes to build an on-the-fly
312 network backbone along with the roads, hence improving the coverage capability while dispensing
313 the stability requirement and the structure creation and maintenance cost. Moreover, we exploit
314 the proposed message propagation pattern to ensure robust relay selection and inhibition rules.
315 Each vehicle could be able to make its own decision on relaying the data in a distributed manner,
316 which opens up the possibility to the envisioned tight coupling of both investigated relay selection
317 mechanisms.

318 **4. System overview**

319 In this section, we will give out an overview of the proposed data dissemination scheme by
320 presenting the following aspects.

Algorithm 1: JV selection process

```
1 // E: The ID of the vehicle that executes the algorithm
2 // CR: The ID of the Current Road in which E is roaming in
3 // stateJV: denotes the current state of E with type pair  $\langle Boolean, string \rangle$ 
4 flag  $\leftarrow$  True
5 J  $\leftarrow$  The ID of the closest Junction associated with CR
6 foreach Neighbor N do
7     if N belongs to one road associated with J then
8         if N closer to J than E then
9             flag  $\leftarrow$  False
10            break
11        end
12    end
13 end
14 if flag = True then
15     // The vehicle becomes a Junction vehicle associated with J
16     stateJV  $\leftarrow$  (True, J)
17 else
18     stateJV  $\leftarrow$  (False, "")
19 end
```

321 *4.1. Assumptions*

- 322 (1) All vehicles are equipped with a DSRC device, static digital map and a positioning system,
323 e.g., GPS receiver. Thus, each vehicle can be aware about its position, velocity and the roads
324 topology.
- 325 (2) Each vehicle is aware about the surrounding one-hop neighbor conditions, such as neighbor
326 identifier, position, velocity, etc. According to the ETSI [5], the latter information can be
327 gathered by means of the Cooperative Awareness Message (CAM) exchanging process and
328 maintained in vehicles' Local Dynamic Map (LDM) [33].
- 329 (3) Vehicles' transmission range is larger than the width of the roads.

330 Notice that assumptions 1 and 2 have been referred by the ETSI [5, 33], as well as assumption
331 3 is reasonable and has been referred by several other works, e.g., in [34, 35].

332 4.2. Node state

333 In the following, we refer to the vehicle that falls closest to a given junction compared to all
334 its neighbors as a Junction Vehicle (JV). A JV incorporates its state and the associated junction
335 identifier inside its CAM messages, notifying its one-hop neighbors about its present state. When
336 receiving a CAM from a JV, each receiver roaming inside one of the roads overlapped in the
337 associated junction considers the sender JV belongs to the same road as it. The goal is to make
338 each JV simultaneously belong to all overlapped roads. The pseudo-code given in Algorithm 1
339 details the JV selection process.

340 4.3. Relays distribution model

341 As described earlier, the key to ensure an efficient message coverage capability is to find how
342 to distribute the relay nodes intelligently inside the AoI. Considering assumption 3, i.e., vehicle's
343 transmission range is larger than the width of road, each road can be considered as a one-dimensional
344 plane [34]. Thus, it is sufficient that a set of potential vehicles distributed parallel to the road line
345 broadcast the message to ensure the coverage of the entire road area, suggesting that the most
346 adaptive relay distribution is parallel to the road line. Besides to the coverage enhancement, the
347 main benefits behind the latter suggestion are two-folds. The former corresponds to the simplicity
348 of realizing this envisioned relay distribution in a distributed manner by enabling a synergy between
349 vehicles to form an on-the-fly backbone network along with the road line. Hence, dispensing the
350 extra overheads incurred by the network structure forming and maintaining phases. The latter
351 corresponds to reducing the signal blocking from the physical obstacles in the road sides e.g., the
352 buildings, advertising boards, vegetation, traffic lights and so on, since the sent messages will be
353 forwarded parallel to the road line. Hence, reducing the channel fading operation and enhancing
354 the relay selection robustness by providing an obstacle avoidance forwarding strategy.

355 4.4. Message propagation pattern

356 In this paper, in order to avoid the chaotic distribution of relays and improve the message
357 coverage capability, we aim to propagate the sent messages based on a specific pattern, further used
358 as the guidance of the relays selection and inhibition rules. Notice that the goal is to achieve the
359 investigated relays distribution model in a distributed manner while considering the characteristics
360 of VANETs. In the beginning, we assume that vehicles are randomly distributed inside the AoI and

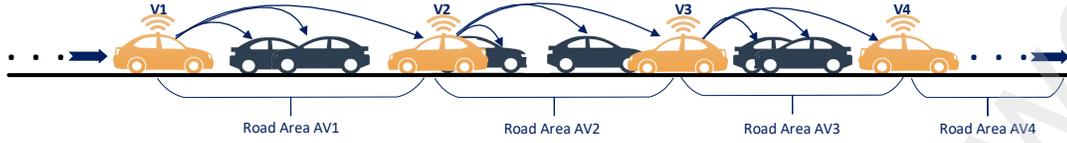


Figure 2: Proposed message propagation pattern over one-dimensional road line

361 a sender node (e.g., vehicle, RSU) triggers the dissemination process by broadcasting an emergency
 362 message. How the receivers deal with the sent message depends on their present states, based on
 363 which the following two cases are discussed.

364 1) *The receiver is not a Junction Vehicle (JV)*: In this case, the receiver follows the in-road
 365 propagation of messages, which is designed to disseminate messages under one road segment, i.e.,
 366 between vehicles roaming inside the same road. As each road can be handled as a one-dimensional
 367 plane, hence the propagation of messages could be at most in two different road line directions.
 368 To do this, our proposed in-road propagation pattern enables messages to be forwarded from the
 369 rear side of the current hop relay towards its front side by means of a front neighbor, and from
 370 the front side of that relay towards its rear side by means of a rear neighbor. To illustrate the
 371 envisioned message propagation pattern, an example is shown in Fig. 2, where we assume that
 372 vehicle V1 is the current hop relay and has received the message from a rear neighbor roaming
 373 inside the same road as it. Based on the above discussion, V1 should forward the received message
 374 towards its front side by means of a potential front neighbor (vehicle V2 in this example). Notice
 375 that, considering assumption 3, the broadcast performed by V1 will cover the entire road area AV1,
 376 where the dimensions of AV1 are proportional to the sender's transmission range for length and
 377 the road width for width. Receiving the message, V2 will find that the previous relay V1 falls in
 378 its front side, hence it will forward the message towards its rear side by means of V3. The same
 379 process is repeated until reaching the last vehicle in that road, basically a JV. In this way, we ensure
 380 the coverage of the entire road progressively area by area with few number of relays and less signal
 381 blocking.

An Elector vehicle E judges whether a Neighbor N falls in its front or rear side based on the angle formed between its velocity vector, denoted as \vec{V}_E , and the line vector \vec{EN} that connects vehicles E and N (represented by Θ in Fig. 3). N is considered as a front neighbor if $\Theta_{E,N} \in [0, 90]$,

and rear neighbor if $\Theta_{E,N} \in]90, 180]$. As vehicles move in two-dimensional plane (X - Y plane), we can write \vec{V}_E and \vec{EN} in their corresponding components as given below,

$$\vec{V}_E = V_{E_x} \hat{i} + V_{E_y} \hat{j} \quad (1)$$

$$\vec{EN} = (x_N - x_E) \hat{i} + (y_N - y_E) \hat{j} = EN_x \hat{i} + EN_y \hat{j} \quad (2)$$

Where (x_N, y_N) and (x_E, y_E) are the geographical coordinates of vehicles N and E respectively. Mathematically $\Theta_{E,N}$ can be calculated by Equation 3 as given below,

$$\Theta_{E,N} = \cos^{-1} \left(\frac{V_{E_x} EN_x + V_{E_y} EN_y}{\sqrt{V_{E_x}^2 + V_{E_y}^2} \sqrt{EN_x^2 + EN_y^2}} \right) \quad (3)$$

382 2) *The receiver is a Junction Vehicle (JV)*: Actually, the in-road propagation of messages enables
 383 a synergy between the relay nodes to build an on-the-fly backbone network parallel to one road line.
 384 In order to merge the overlapped in-road backbones and make messages able to spread over the
 385 entire AoI, an inter-roads propagation of messages should be performed by splitting the message
 386 into multiple copies and comprehensively switching them towards the uncovered roads. In this work,
 387 we refer to the JVs as the most potential vehicles to perform the latter task for two main reasons:
 388 their ability to be simultaneously belong to all overlapped in-road backbones, and particularly their
 389 potentiality to perform the inter-roads propagation of messages without intersecting the physical
 390 obstacles in the road sides. This is because the JVs are the most likely to be within the intersection
 391 zones, i.e., the zones with less radio obstacles.

392 4.5. Forwarding algorithm

393 In contrast to most of the existing dissemination schemes that were designed to operate exclu-
 394 sively based on either a sender-oriented or receiver-oriented relay selection mechanism, we rather
 395 aim to take advantages of both investigated mechanisms by combining them in one hybrid scheme.
 396 When one vehicle receives the message, it first needs to judge whether or not the message propaga-
 397 tion pattern has been fulfilled under its coverage area by comparing the different angles of arrival
 398 of the sent message. If yes, meaning that the message has been successfully propagated under its
 399 vicinity and the vehicle is a noncritical relay candidate, it will discard the received message. Other-
 400 wise, it determines its relevance for relaying the message by computing a back-off timer associated
 401 with the following priority assignment metrics. First, we assign the shortest back-off timers to the

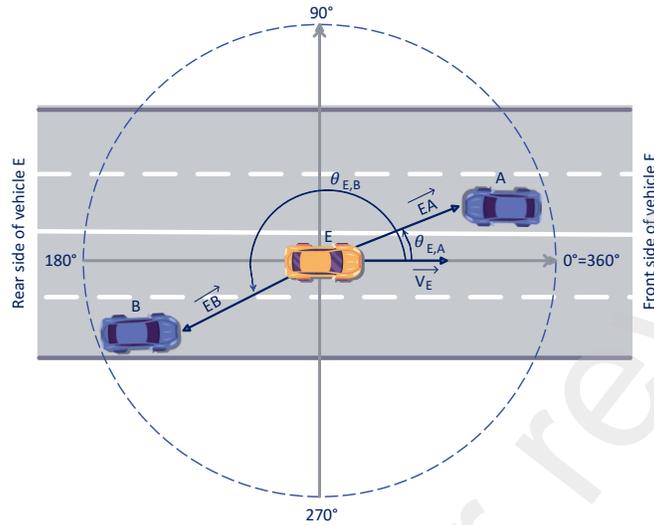


Figure 3: Front and rear neighbors determination

402 explicitly selected relays, hence enabling a continuous retransmissions at the application layer to
 403 ensure a short latency. To do this, each vehicle behaving as a relay node should incorporate its
 404 own associated relay list inside the message before broadcasting it. On the other hand, in order
 405 to avoid the explicit relay selection shortcomings, especially the poor reachability incurred by the
 406 unexpected link failure problem, we adopt one new recovery strategy inherited from the receiver-
 407 oriented mechanism. Each receiver that has not been explicitly selected to relay the message and
 408 falls in its propagation direction should monitor the propagation of the sent message. If a recovery
 409 timer is expired and the message propagation pattern was not fulfilled under the receiver's vicinity,
 410 which means that a link failure has been occurred, the receiver will compensate for this issue by
 411 relaying immediately the message. In other words, the proposed forwarding algorithm provides a
 412 tight coupling between both existing relay selection mechanisms by enabling vehicles to collabo-
 413 ratively handle the multi-hops retransmissions of messages in an efficient manner. Hence, besides
 414 to the coverage enhancement, messages could be forwarded rapidly with few overheads and high
 415 reachability rate.

416 5. Proposed BACKNET-HSR data dissemination scheme

417 In light of the above description, this section details the proposed BACKNET-HSR scheme.
418 The flowchart depicted in Fig. 5 presents the whole dissemination process of our scheme, which
419 includes the following parts.

420 5.1. Inhibition rule

421 As mentioned earlier, consider a flat network structure, the lack of an efficient message propaga-
422 tion pattern leads to an indiscriminate inhibition of the relay candidates, resulting in a poor message
423 coverage capability. To deal with this problem, each vehicle should make its own decision on relay-
424 ing the data in a distributed manner based on its potentiality for realizing the envisioned message
425 propagation pattern under its coverage area. To do this, each vehicle monitors the propagation
426 of the sent message under its coverage area and infers whether or not the envisioned propagation
427 pattern has been fulfilled in that area. By assuming that a given vehicle heard the transmissions of
428 the same message from two neighbors falling in the two different road line sides (i.e., front and rear
429 neighbors), hence it can be deduced that the vehicle should not be considered as a potential relay
430 candidate, since the expected in-road backbone has been already built inside its monitoring area.
431 Otherwise, if the vehicle has received the message from neighbor(s) falling in one road line side,
432 meaning that a disconnection of the envisioned in-road backbone has been occurred, the vehicle
433 becomes a critical relay candidate due to its high potential for fixing the disconnection issue by
434 relaying the message towards the uncovered road side. As a result, as shown in Fig. 5 (left dotted
435 rectangle), the only case in which a vehicle becomes inhibited to relay the message is the fulfillment
436 of the message propagation pattern under the vehicle's vicinity, which is achieved when hearing the
437 transmission of the same message from at least two neighbors falling in two different road line sides.

438 5.2. Explicit selection of relays

439 In order to handle the delay sensitive VANET-based applications, the sender-oriented relay
440 selection mechanism has been exhibited as a promising solution to spread data rapidly over multiple
441 depots. By adopting the explicit selection of relays, a continuous retransmission at the application
442 layer can be realized. The sender nodes should incorporate the identifiers of the next dissemination
443 entities inside the disseminated data, which will be able to rebroadcast immediately. Because
444 of the unique characteristics of VANETs, ensuring a good network reachability represents the

445 major challenge of the explicit selection of relays. Thus, taking into account the robustness of
446 the forwarding links during the process of relays selection is quite important for enhancing the
447 data delivery capability. Next, we will introduce our proposed relay selection metrics for improving
448 reachability, then we will detail the explicit relays selection algorithm.

449 5.2.1. Relay selection metrics

450 As discussed in [36], the mobility metrics show better performance results in the context of a
451 good network reachability in VANETs. For this reason, we aim to provide sufficient connection
452 duration between neighboring relays by considering the mobility of vehicles. Thus, improving the
453 stability of the wireless link connections and mitigating the rapid link failure problem. On the
454 other hand, as roads are not always straight, we aim to fit the strip-shaped roads by taken into
455 account the curvature of the road lines when selecting the next hop relays. The goal is to realize
456 our envisioned obstacle avoidance forwarding strategy in different road line geometries without
457 exploiting the received radio strength (RSS) metric that were considered as unsuitable in VANETs
458 due to its poor precision [36, 37]. Additional solutions for improving reachability could be included
459 in our relay selection metrics, but remind that we focus on the recovery strategy to achieve this
460 goal, as described in Section 5.3. The proposed relay selection metrics are described as follow:

461 1) *Distance factor*: In order to achieve the desired coverage with few number of relays, we
462 exploit the greedy forwarding algorithm to assign priority to the neighbors further away from the
463 elector for becoming relay nodes. However, considering the high mobility constraints, the greedy
464 mode easily lead to an unexpected link failure problem [38, 39] since the farthest away (i.e., the ones
465 that fall closer to the communication radius of the elector vehicle) are the most likely to be moved
466 outside the elector's communication radius, resulting in a poor reachability between neighboring
467 relays. To cope with this problem, we tend to adjust the greedy algorithm with the mobility of
468 vehicles for ensuring stable communication links. To achieve this goal, we assign priority to the
469 neighbor falling furthest in distance and remaining within the transmission range of the elector
470 vehicle for a given period of time, measured as the time interval between two successive beacon
471 messages (referred to as Δt). Thus, the distance factor $\overline{d_{E,N}}$ between an elector E and its neighbor
472 N can be computed as:

$$\overline{d_{E,N}} = 1 - \frac{\left| \sqrt{(x_E - x_N)^2 + (y_E - y_N)^2} - d_{opt} \right|}{d_{opt}}, \quad (4)$$

where (x_N, y_N) and (x_E, y_E) denote the geographical coordinates of vehicles N and E respectively, and d_{opt} stands for the optimal distance between two neighboring relays which can be evaluated as:

$$d_{opt} = d_{max} - \frac{d_{max}}{2v_{max}\Delta t},$$

where d_{max} denotes the maximum transmission range of the adopted DSRC device, and v_{max} represents the allowed maximum speed of vehicles.

2) *link straightness factor*: The goal behind this evaluation factor is to comprehensively adjust the relays distribution according to the road line curvature, thus maximizing the dissemination coverage capability over one road-segment, as well as ensuring our envisioned obstacle avoidance forwarding strategy even in case of strip-shaped roads. To do this, we first exploit the mobility direction of the elector vehicle as an indicator of the road curvature. To be noted that the movement trajectory of vehicles is basically parallel to the road line. Then, we tend to assign priority to the neighbor where the angle between its location and the elector's velocity vector, i.e., the angle Θ described in Equation 3, approaches to 0 (*zero-angle*) or 360 (*complete-angle*) for becoming an associated Frontal Relay Node (FRN). On the other side, the neighbor that forms a straight angle (i.e., approach to 180) is more likely to play the role of associated Rear Relay Node (RRN). For the purpose of the link straightness factor evaluation, the elector assigns priorities to the neighbors with the optimal angle $\overline{\Theta_{E,N}}$. How to compute $\overline{\Theta_{E,N}}$ depends on the state of the associated relay candidate, i.e., FRN or RRN candidate, as given below,

$$\overline{\Theta_{E,N}} = \begin{cases} 1 - \frac{\Theta_{E,N}}{90} & , \Theta_{E,N} \in [0, 90] \\ \frac{\Theta_{E,N}}{180} & , \Theta_{E,N} \in]90, 180] \end{cases} \quad (5)$$

Where $\Theta_{E,N}$ stands for the angle Θ described in Equation 3.

5.2.2. Relay selection algorithm

Actually, Designing an efficient message propagation pattern opens up the possibility of a proactive selection of relays, hence dispensing the computation overload during the dissemination process. In fact, based on the investigated propagation pattern, the network backbone can be constructed

493 in a proactive manner by enabling each vehicle to proactively build its own Associated Relays List
 494 (ARL) based on the information gathered from the received CAM messages. Then, upon behaving
 495 as a relay node, the vehicle incorporates its own ARL inside the message and broadcasts it. How to
 496 elect the associated relays depends on the vehicle's status, based on which the following two cases
 497 are distinguished.

498 1) *The vehicle is not a JV – Algorithm 2:* In this case, the vehicle could follow the in-road
 499 propagation pattern. It elects, among the neighbors roaming inside the same road as it, the most
 500 potential one falling in its front side as an associated Frontal Relay Node (FRN), and the most
 501 potential one falling in its rear side as an associated Rear Relay Node (RRN).

502 2) *The vehicle is a JV – Algorithm 3:* In this case, the JV is intended to perform the inter-road
 503 propagation of messages. For each set of neighbors roaming inside such an overlapped road, it elects
 504 the most potential one as an associated relay, i.e., one potential neighbor for each overlapped road.

505 An elector vehicle E determines the capacity of each associated relay candidate N based on the
 506 above relay selection metrics, as given below:

$$\omega_{f_{E,N}} = \begin{cases} \alpha \overline{d_{E,N}} + (1 - \alpha) \overline{\Theta_{E,N}} & , \text{if } E \text{ is a } JV \\ \overline{d_{E,N}} & , \text{Otherwise} \end{cases}, \quad (6)$$

507 where α represents a weight parameter such that $\alpha \in [0, 1]$. In this work, we tend to dominate the
 508 distance influence factor by setting α to 0.8, as the most adaptive value in our simulation study.

509 At this point, it can be noticed that the ARL is composed of at least two associated relays,
 510 e.g., FRN and RRN. Hence, it is obvious that the fact of selecting more than one neighbor to relay
 511 the sent message could easily incur the simultaneous retransmissions and hidden nodes problems.
 512 To solve these issues, we adopt an index-based timer that enables the explicitly selected relays to
 513 schedule their transmissions for a T_{send} timer, computed based on the relay's index in the received
 514 ARL. The one with index zero rebroadcasts immediately, the second rebroadcasts after λt delay,
 515 and so on. T_{send} is calculated as given below,

$$T_{send} = i_j \lambda t, \quad (7)$$

516 where i_j denotes the index of the explicitly selected neighbor N_j in the ARL, and λt represents one
 517 waiting time slot.

Algorithm 2: Associated relays selection process: the vehicle is not a JV

```
1 //  $E$ : The ID of the vehicle that execute the algorithm
2 //  $CR$ : The ID of the road in which  $E$  is roaming in
3 if  $stateJV.first = True$  then
4   goto Algorithm 3
5   return
6 end
7  $\omega_{FRN}^{max}, \omega_{RRN}^{max} \leftarrow 0$ 
8 Map  $\langle string, address \rangle MAP \leftarrow null$ 
9 foreach Neighbor  $N$  do
10  if  $N$  falls in  $CR$  then
11     $\Theta_{E,N} \leftarrow$  Compute the angle  $\Theta$  as given in Equation 3
12     $\omega_{E,N} \leftarrow$  Compute  $\omega_{E,N}$  as given in Equation 6
13    if  $\Theta_{E,N} \in [0, 90]$  then
14      //  $N$  will be handled as an FRN candidate
15      if  $\omega_{E,N} > \omega_{FRN}^{max}$  then
16         $\omega_{FRN}^{max} \leftarrow \omega_{E,N}$ 
17         $MAP \leftarrow insert('FRN', N.address)$ 
18      end
19    else
20      //  $N$  will be handled as an RRN candidate
21      if  $\omega_{E,N} > \omega_{RRN}^{max}$  then
22         $\omega_{RRN}^{max} \leftarrow \omega_{E,N}$ 
23         $MAP \leftarrow insert('RRN', N.address)$ 
24      end
25    end
26  end
27 end
28  $ARL \leftarrow MAP$ 
```

518 *5.3. Implicit selection of relays*

519 Basically, considering the unique characteristics of VANETs, it is complex to guarantee robust
520 wireless link between mobile vehicles. In other words, important packet loss still occurred because
521 of the unexpected link failure problem, even-though taken into account multiple link condition
522 parameters. Thus, adopting one new recovery strategy for compensating the lost packets while not
523 increasing the dissemination delay is quite important to enhance the dissemination efficiency. To

Algorithm 3: Associated relays selection process: the vehicle is a JV

```
1 // E: The ID of the vehicle that execute the algorithm
2 // J: The Junction ID that the junction vehicle E associated with
3 Map < string, address > MAP ← null
4 foreach Road  $R_i$  associated with J do
5    $\omega f_{E,N}^{max} \leftarrow 0$ 
6   foreach Neighbor N roaming in  $R_i$  do
7      $\omega f_{E,N} \leftarrow$  Compute  $\omega f_{E,N}$  as given in Equation 6
8     if  $\omega f_{E,N} > \omega f_{E,N}^{max}$  then
9        $\omega f_{E,N}^{max} \leftarrow \omega f_{E,N}$ 
10       $MAP \leftarrow insert(R_i.ID, N.address)$ 
11    end
12  end
13 end
14  $ARL \leftarrow MAP$ 
```

524 achieve this goal, we first adjust our proposed inhibition rule with the message propagation pattern
525 perspectives by making all vehicles able to monitor the propagation of the sent message under their
526 transmission ranges. Then, each vehicle could make its own decision on relaying the message in
527 a distributed manner, independently on whether or not they are explicitly selected to relay the
528 data. One simple and efficient solution to implement this is to let every vehicle receiving the sent
529 message and fall in its propagation direction to hold it, and schedule a recovery timer, denoted as
530 T_{rec} , computed as:

$$T_{rec} = T_{rec}^{max} \left[\alpha \left(1 - \frac{d_{R,P}}{d_{max}} \right) + (1 - \alpha)(1 - \overline{\Theta_{R,P}}) \right], \quad (8)$$

where T_{rec}^{max} denotes the maximum recovery timer value; $d_{R,P}$ represents the distance between the Receiver R and the Previous relay node P, computed as:

$$d_{R,P} = \sqrt{(x_P - x_R)^2 + (y_P - y_R)^2},$$

531 where (x_N, y_N) and (x_P, y_P) denote the geographical coordinates of vehicles N and P respectively;
532 and $\overline{\Theta_{R,P}}$ stands for link straightness factor, computed as given by Equation 5. In order to ensure
533 robust relay selection process, remark that both implicit and explicit relay selection metrics are
534 compliant with each other, except of the mobility parameters since the implicit selection has no

535 requirement with the stability of the link connection.

536 If T_{rec} expires and no inhibition occurred, i.e., the vehicle captures a link failure, the vehicle
537 recovers quickly this issue by immediately broadcasting the message. A vehicle considers itself as
538 falling in the message propagation direction if it is not inhibited to broadcast and has received the
539 message from neighbor roaming inside the same road as it.

Besides, as VANETs have a time-varying density, we introduce an additional timer, namely Backup or T_{bkp} , for fitting the sparse network scenario where the density of vehicles is not enough to ensure the envisioned propagation of messages. In this way, vehicles that receive for the first time the sent message and do not fall in its propagation direction will schedule their transmission for a backup timer, which is computed as given below:

$$T_{bkp} = T_{bkp}^{max} + \mu(0, 0.1), \quad (9)$$

540 where T_{bkp}^{max} denotes the maximum backup timer value, and $\mu(0, 0.1)$ represents an uniformly dis-
541 tributed random component to avoid the simultaneous retransmissions problem. If the vehicle is
542 not inhibited after elapsing T_{bkp} time, meaning that a network partition is captured, the vehicle
543 should immediately relay the message inside the road that is belonging to.

544 5.4. A case study

545 To illustrate the proposed dissemination scheme, an example scenario is shown in Fig. 4, where
546 we assume that the Source Vehicle SV starting the dissemination process. In the beginning, SV
547 incorporates its ARL, e.g., JV1 as FRN and V2 as RRN, and broadcasts the message. Receiving
548 for the first time the sent message from one neighbor roaming inside the same road as them, all the
549 receivers V2, V5, V15-V18 and JV1 are considered as falling in the message propagation direction.
550 Thus, the explicitly selected relays JV1 and V2 should schedule their transmissions for T_{send} , while
551 the others schedule their recovery timers T_{rec} . Having a JV status, the ARL of JV1 is formed based
552 on the inter-road propagation of messages by selecting one vehicle for each overlapped road, i.e.,
553 vehicles V5, V12-V14. Upon hearing the broadcast performed by JV1, the vehicles V5, V17 and
554 V18 should immediately cancel their scheduled transmission, since the message propagation pattern
555 has been already fulfilled in their transmission range by receiving twice copies of the same message
556 from neighbors falling in two different road line directions (SV and JV1). As JV1 simultaneously
557 belongs to all the overlapped roads, the explicitly selected relays V12-V14 broadcast after T_{send} ,

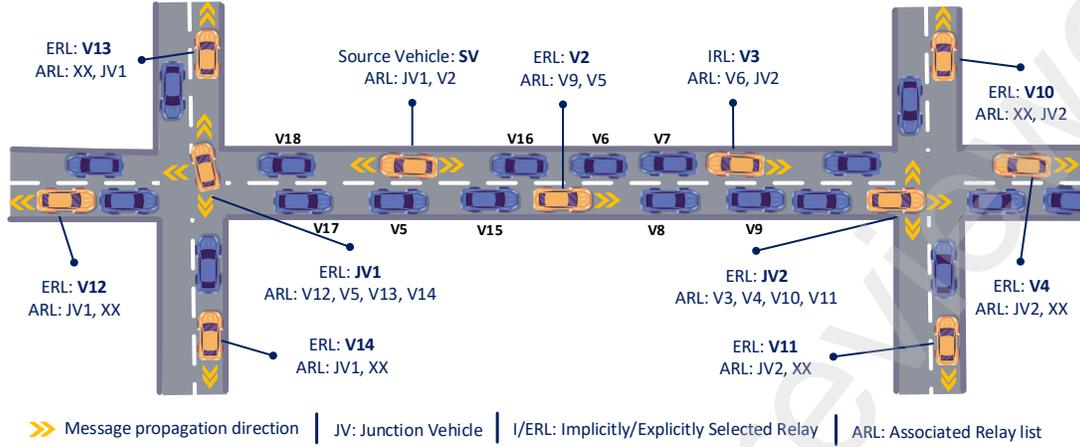


Figure 4: Example of the proposed dissemination scheme

558 while the other receivers schedule T_{rec} . For example, V13 finds that the message was received from
 559 a rear neighbor, hence it should forward it towards its front side. Similarly, V2 forwards the message
 560 towards its front side by means of its FRN V9. However, in order to activate the implicit selection
 561 of relays, we assume that V9 has been moved outside the communication radius of V2, hence, it
 562 does not hear the transmission made by V2. Following the investigated implicit relays selection
 563 algorithm, vehicles V3 and V6-V8 are falling in the propagation direction of the message forwarded
 564 by V2, hence they schedule their transmission for T_{rec} . Consider that V3 has the shortest T_{rec} and
 565 V9 does not broadcast, V3 will be an implicitly selected relay. Notice, that the broadcast made
 566 by V3 will make the monitored message propagation pattern of vehicles V6-V8 fulfilled, which will
 567 force them to cancel their scheduled transmissions. The same process is repeated until ensuring the
 568 coverage of the entire AoI.

569 6. Performance evaluation

570 In this section, we present the performance assessment of our proposed solution using the OM-
 571 NET++ 5.6.2 network simulator [40]. The proposed BACKNET-HSR protocol is compared to
 572 the current standard of data dissemination in VANETs, CBF [9], and the sender-oriented BDSC
 573 scheme with the variant (LQ×d) as the most efficient approach compared to the other convolution
 574 schemes proposed in [14]. We generate the mobility of vehicles using the road traffic simulator

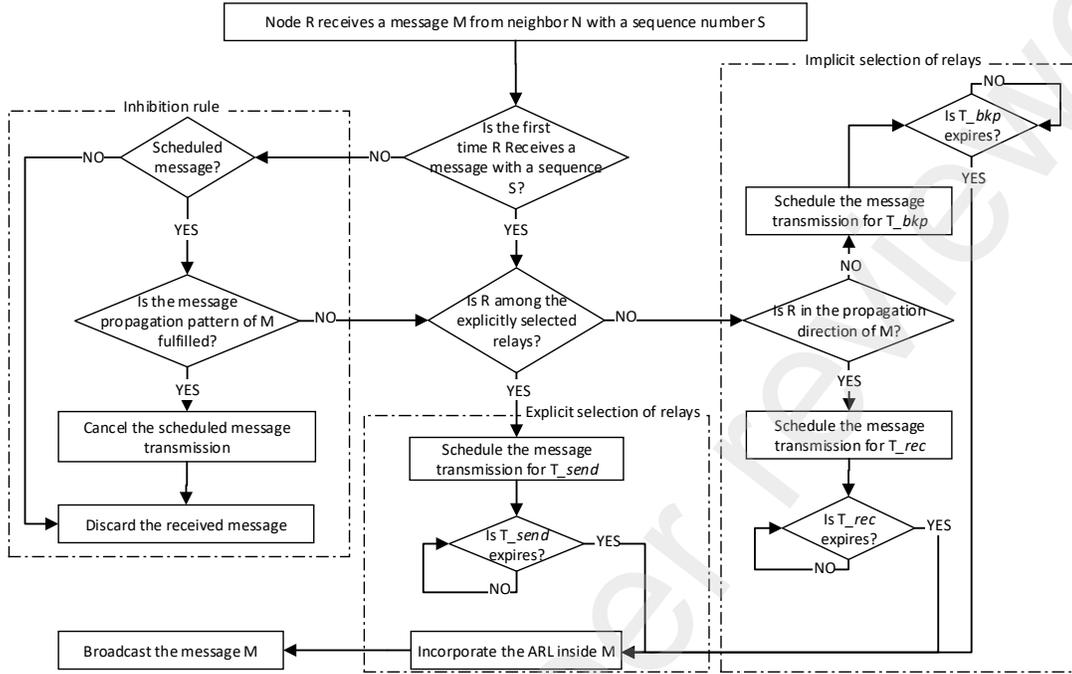


Figure 5: The flow chart of the proposed Dissemination scheme

575 SUMO 1.8.0 [41]. OMNET++ is coupled with SUMO by using Veins 5.1 [42], a popular network
 576 simulator framework that implements the required protocol stacks and other relevant features of
 577 the vehicular communication process, such as the IEEE 802.11p communication technology and the
 578 channel fading operation.

579 6.1. Simulation scenario

580 For evaluation purposes, we consider two urban simulation scenarios. The first simulation study
 581 is performed under a Manhattan grid scenario comprised of 81 evenly-spaced intersections in an
 582 area of $2,5 \text{ km}^2$ with bidirectional roads. The second simulation study is performed under a more
 583 realistic scenario known as Luxembourg SUMO Traffic (LuST) Scenario [43, 44] in an area of 2
 584 $\text{km} \times 2,5 \text{ km}$ square. The vehicular traffic is generated randomly according to the random trips
 585 model provided by SUMO. The maximum speed of each vehicle is around 14 m/s.

586 In this simulation study, we consider six different vehicles densities ranging from 30 to 125

Table 2: Main simulation parameters

Parameter	Value
Simulation time	120 s
Mac model	IEEE 802.11p
Vehicle density	30-125 vehicles/km
Maximum transmission power	3 mW
Maximum transmission range	$\simeq 250$ m
Bit rate	6 Mbit/s
Carrier frequency	5.89 GHz
Beacon size	32 Bytes
Beacon frequency	1 /s
α	0.8
λt	0.01
d_{max}	250 m
v_{max}	14 m/s
t_{rec}^{max}	0.1 s
t_{bkp}^{max}	0.02 s

587 vehicles/km. Each simulation experiment lasts 120 s (with 20 s of warm-up period), where the
588 dissemination process is triggered every 10 s from 10 randomly selected vehicles. Each disseminated
589 message comprises 1024-byte data, which represents an emergency warning message to notify the
590 vehicles roaming inside the area of interest. In order to assess the dissemination performance under
591 a large scale network, we consider the whole network region as area of interest. Each simulation
592 experiment is repeated 5 times with random sender vehicles, from which we obtain the mean value
593 of each point in the graph. The main simulation parameters are summarized in Table 2.

594 6.2. Performance metrics

595 As mentioned in [45, 46], messages in VANETs should be spread rapidly with high delivery
596 capability and efficient utilization of the radio interface. For this reason, our performance assessment
597 of all three investigated protocols is based on the following metrics:

- 598 • **Dissemination coverage:** The ratio of the successfully receiving nodes from the total num-
599 ber of nodes roaming inside the area of interest.
- 600 • **Dissemination Delay:** The average elapsed time that a message takes to reach a given

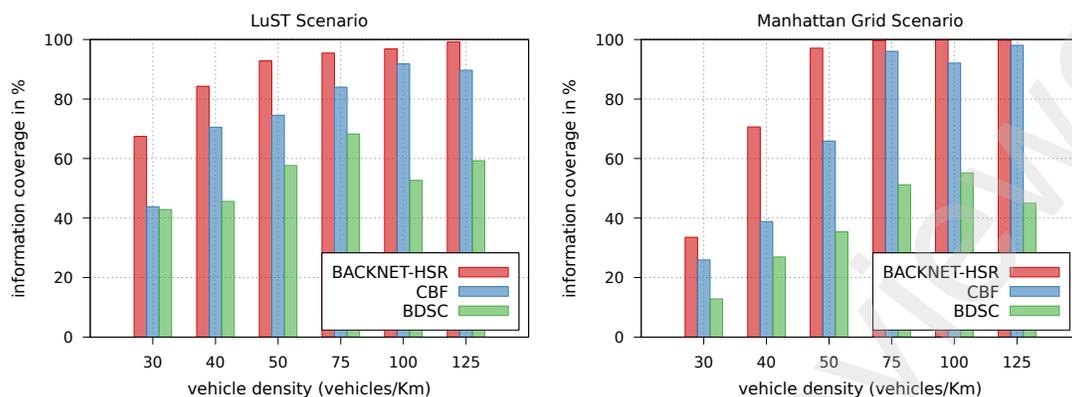


Figure 6: Information coverage ratio vs. vehicle density.

601 destination node.

- 602 • **Saved Rebroadcasts:** This metric is used to determine the usage efficiency of the radio
603 interface [47], it determines the percentage of nodes that did not rebroadcast the message.
604 Hence, the more the rebroadcasts are saved, the lower the allocation and contention on the
605 shared channel.

606 6.3. Numerical results and performance analysis

607 Fig. 6 shows the dissemination coverage ratio among three protocols for varying vehicular den-
608 sities under the Manhattan-Grid and LuST scenarios. From this figure, it is apparent that the
609 dissemination coverage is less effective in low node densities. The reason is that in poor vehicle
610 density, the network connectivity can not be ensured, hence the probability of finding one complete
611 routing path between two far nodes becomes low. For a better clarification of this case, Fig. 7 shows
612 the dissemination coverage as a function of the distance from the originator vehicle (i.e., the vehicle
613 that trigger the disseminated message) under the sparse network scenario, e.g., node density ≤ 50
614 vehicles/Km. For the lowest vehicular density (30 vehicles/km), the information coverage is sharply
615 decreasing as the distance from the originator vehicle increase. This means that the higher the dis-
616 tance from the sender, the smaller the number of available links within that distance. In average, it
617 can be observed that our proposed BACKNET-HSR exhibits much better performance compared
618 to CBF and BDSC for both considered scenarios under the sparse networks. For a node density
619 ≤ 50 vehicles/km under the LuST scenario, BACKNET-HSR can reaches on average more than 81%

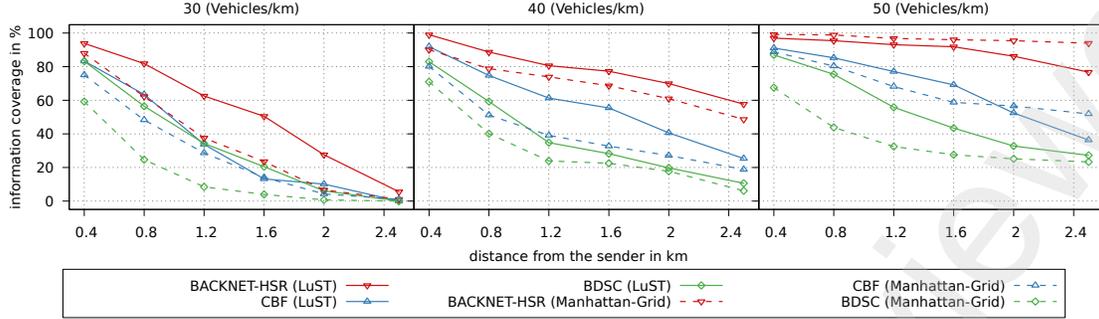


Figure 7: Mean information coverage vs the distance from the originator vehicle for different low vehicular density scenarios.

620 of the participating vehicles, while only 60% and 48% of vehicles are covered by CBF and BDSC
 621 respectively. In reality, this is already expected since both CBF and BDSC adopt an indiscriminate
 622 inhibition of the relay candidates (please refer to section 3), which becomes a serious problem when
 623 the number of available next hop relays is small. Also, we can see that the indiscriminate inhibition
 624 effect is more remarkable under the Manhattan Grid scenario, where BACKNET-HSR improves
 625 the dissemination coverage by approximately 24% and 42% with respect to CBF and BDSC. This
 626 is due to the fact that vehicles under the Manhattan Grid scenario follow only a vertical and hor-
 627 izontal distribution with sufficient spaces between parallel road lines to minimize the variety of
 628 available next hop relays in terms of polar distribution, making the issues described in Fig. 3 more
 629 reproducible. Summing up, BACKNET-HSR exhibits much better performance in terms of the
 630 coverage capability compared to CBF and BDSC for the low vehicular densities scenarios. For
 631 instance, it can achieve more than 90% of the coverage ratio under relatively sparse networks (e.g.,
 632 50 vehicles/km) while only 75% and 68% of vehicles are covered in CBF and BDSC respectively,
 633 which suggests that considering the vehicular distribution brings a significant enhancement in terms
 634 of the dissemination coverage.

635 By increasing vehicle density, the network fragmentation becomes less possible and the number
 636 of available links toward far vehicles increases, resulting in the improvement of the coverage ratio
 637 for all the protocols as shown in Fig. 8. However, for the case of CBF, when exceeding one density
 638 threshold, e.g., vehicle density = 100 vehicles/km for the LuST scenario, the coverage ratio starts
 639 to decline as the distance from the originator increases. The reason is that CBF adopts a distance

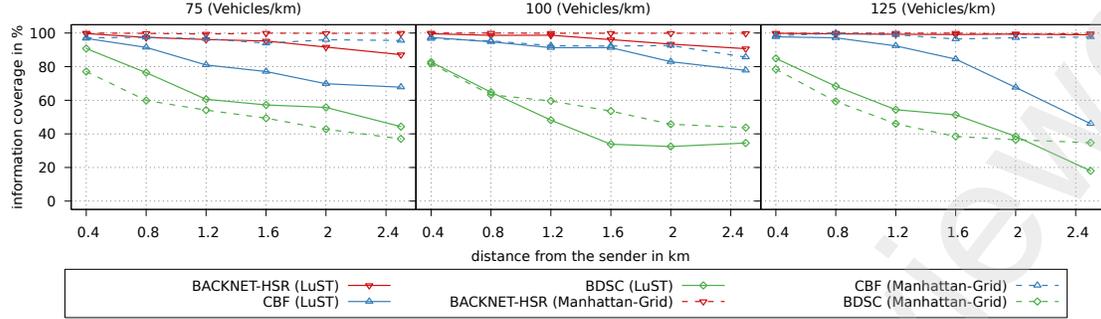


Figure 8: Mean information coverage vs the distance from the originator vehicle for medium to high vehicular density scenarios.

640 based relays selection mechanism, hence the probability of finding equidistant neighbors from the
 641 sender (i.e., with equal transmission timers) in dense scenario is high. As a result, more data
 642 collision will occur because of the simultaneous rebroadcasts from nearby nodes, which subvert the
 643 availability of the network and affect the coverage capability. This problem is less likely to occur
 644 in the Manhattan grid scenario since, as described earlier, the neighbors of each sender vehicle (i.e.
 645 the contender nodes) can be only distributed following a vertical and/or horizontal road structures.
 646 Hence, the number of contender vehicles having similar retransmission timer is reduced, which
 647 explains the robustness of CBF's coverage performance in dense scenarios under the Manhattan
 648 grid scenario. As shown in Fig. 8, BDSC has an inconsistent coverage performance since it highly
 649 depends on the availability of the selected next hop relays.

650 By comparison, besides to the indiscriminate selection of relays, BDSC adopts only an explicit
 651 selection of relays, making it the most affected by the issue of the frequent disconnection of the
 652 communication links. As a result, BDSC exhibits the worst performance compared to the other
 653 schemes. In CBF, the indiscriminate selection and inhibition of relays leads to low dissemination
 654 coverage, especially under sparse scenarios. In contrast, in case of dense network, the number of
 655 contender nodes will considerably increase, leading to a serious packets collision problem. As for
 656 BACKNET-HSR, by adopting a hybrid selection of relays while respectively adjusting the relays
 657 distribution according to the road lines geometry, the latter exhibits the best robustness for varying
 658 traffic densities and for different simulation scenarios. Thus, independently from the considered
 659 scenario, BACKNET-HSR is able to cover on average more than 85% of vehicles, as the most

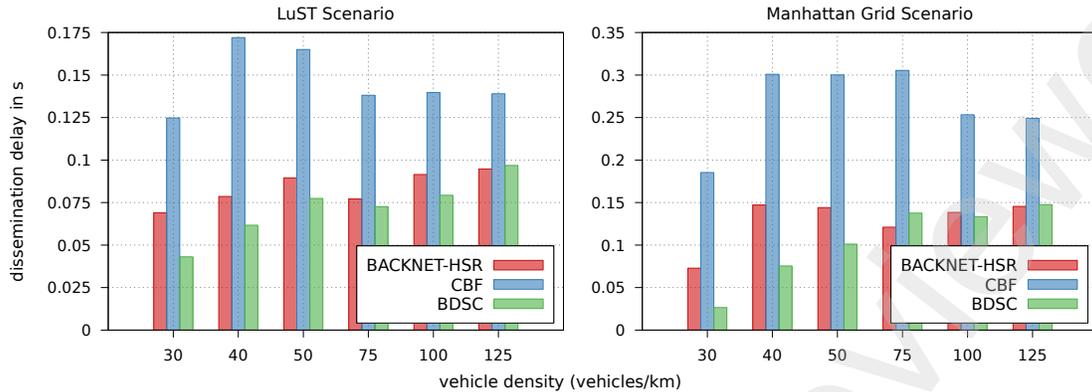


Figure 9: Dissemination delay ratio vs. vehicle density.

660 effective scheme in terms of the dissemination coverage.

661 Fig. 9 illustrates the average dissemination delay for different node densities. As expected,
 662 CBF has the worst performance for both scenarios, since it involves the contention windows before
 663 each retransmission. Compared to BDSC, BACKNET-HSR not only adopts the sender-oriented
 664 mechanism during the dissemination process, but also propose the use of the receiver-oriented
 665 mechanism as a recovery strategy, thus it adds some extra delay that varies according to the
 666 vehicular traffic densities. In fact, for low traffic density (e.g., for 30 vehicles/Km, case of the
 667 Manhattan grid), BACKNET-HSR has twice higher dissemination delay compared to BDSC, while
 668 they have approximately equivalent delay in case of dense network (e.g., for 125 vehicles/Km of the
 669 same scenario). This is simply due to the backup mechanism adopted by BACKNET-HSR that is
 670 more used as the node density decreases. As can be seen from Fig. 9, the dissemination delays are
 671 much higher for the Manhattan Grid for all three protocols. This is simply because there is less
 672 diversity of next relay candidates in the Manhattan grid scenario, hence the sent messages require
 673 much more number of hops for reaching vehicles far away from the originator.

674 For all three protocols, the lowest delay was achieved when the node density is very low (i.e., 30
 675 vehicles/Km). The main reason is that, according to Fig. 7, the dissemination coverage is restricted
 676 only to a subset of close nodes, which basically requires few number of retransmissions to be fully
 677 covered. They reach a peak when the network density is approximately comprised between 40-
 678 75 vehicles/Km (vary according to the considered scenario and/or scheme). In fact, as shown in
 679 Fig. 6, the real beginning of the coverage enhancement has occurred with these densities range,

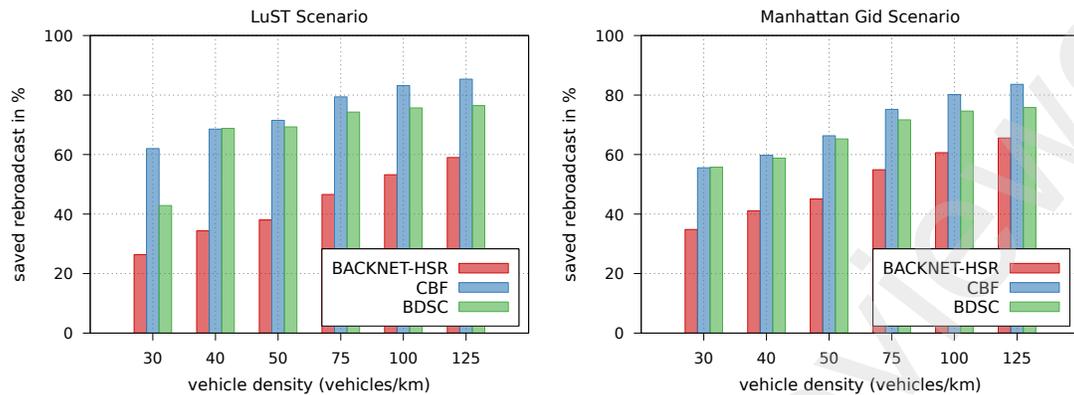


Figure 10: Saved rebroadcasts ratio vs. vehicle density.

680 meaning that the density becomes higher enough to cover vehicles relatively far away from the
681 message originator. However, it does not become higher enough to ensure the optimal behavior
682 of the dissemination process, especially for CBF and in smaller proportion for BACKNET-HSR
683 and BDSC. For CBF, the involved back-off timers depend on the distance from the sender nodes.
684 As a result, for low and medium densities, there is no guarantee to find one neighbor far enough
685 from the sender to ensure the rapid propagation of messages. Therefore, the near neighbors are
686 responsible for rebroadcasting the sent message, however with an expended back-off timers. As
687 already stated, the delay incurred by BACKNET-HSR in that range of node densities is mainly
688 due to the adopted backup mechanism, designed to compensate the mismatching of the envisioned
689 propagation pattern with the low vehicular densities. BDSC appears as the less affected by this
690 phenomena, because it adopts a simple sender-oriented dissemination process. By increasing the
691 network density, we reach the optimal behavior of the dissemination process, which can noticeably
692 reduce the transmission delay. However, when exceeding one threshold, e.g., 75 vehicles/Km for
693 the Lust scenario, we observe a slight increase in the transmission delay. Actually, this fact can be
694 attributed to the collision problem in dense vehicular scenarios as described earlier, since the delay
695 mounting can be due to the channel allocation and competition caused by the extra overhead in
696 these particular scenarios. This rise in delay is less remarkable under the Manhattan Grid scenario
697 since, as stated before, the collision problem is less likely to be occurred in this scenario.

698 Fig. 10 illustrates the saved rebroadcasts ratio for the investigated protocols and for varying
699 vehicular densities under both considered scenarios. For BACKNET-HSR, due to the proposed

700 propagation pattern, the number of rebroadcasts mainly depends on the considered road maps
701 topology. The higher the number of roads, the higher the number of rebroadcasts. On the other
702 hand, the broadcast decision in CBF and BDSC is mainly based on the distance and/or the link
703 stability factors, independently from how the vehicular traffic is distributed. This is confirmed
704 by the fact that the saved-rebroadcasts of BACKNET-HSR are noticeably improved under the
705 Manhattan Grid scenario (the one with the lowest number of roads), while it remains the same for
706 the other investigated protocols.

707 In general, as can be seen in both considered scenarios, BACKNET-HSR has the lowest saved-
708 rebroadcasts, especially in case of sparse networks (the case where BACKNET-HSR noticeably
709 improves the information coverage). In reality, this suggests the trade-off between the coverage
710 requirement and the overhead constraints. Meanwhile, it is observed from Fig. 10 that the increase of
711 the traffic density leads to more and more convergence between BACKNET-HSR and the two other
712 protocols, which means that BACKNET-HSR exhibits more robustness with respect to the traffic
713 density variation. In other words, in order to achieve better dissemination coverage, the propagation
714 pattern designed for BACKNET-HSR tends to fit the road topology maps, independently from the
715 vehicular traffic density. In fact, in low and medium densities (≤ 75 vehicles/Km) for all three
716 protocols, the amount of the saved-rebroadcasts is increased linearly with the increase of the traffic
717 density. However, for CBF and BDSC, this improvement becomes less remarkable when exceeding
718 that range of densities (> 75 vehicles/Km). For the case of CBF, this confirms our previous analysis
719 about its poor performance in terms of information coverage and delay in dense networks, since the
720 packets collision are basically steaming from the simultaneous rebroadcasts among vehicles with
721 similar back-off timers, resulting in an additional communication burden. In BDSC, the adopted
722 relays selection algorithm is highly dependent on the link quality between vehicles. This means
723 that, in dense networks, it is more likely that a given relay elects its near neighbors as the next
724 relaying vehicles, which can noticeably increase the number of multi-hop retransmissions.

725 **7. Conclusion**

726 In this work, we developed a Robust BACKbone NETwork based on Hybrid Selection of Re-
727 lays (BACKNET-HSR) to solve a series of challenging problems of data dissemination in VANETs.
728 The goal is to ensure the timely delivery of public interest messages under different traffic densi-
729 ties and complex urban scenarios. Firstly, we aim to overcome the problems stemming from the

730 chaotic distribution of relays by designing an efficient relays distribution model suitable to the city
731 settings and some specific characteristics of VANETs. The relays selection and inhibition rules
732 are comprehensively adjusted to realize the envisioned distribution model in a distributed manner
733 and without any extra overheads. To do this, we design one new message propagation pattern to
734 build an on-the-fly backbone network that integrates a subset of potential relay nodes distributed
735 parallel to the road lines, enabling messages to be disseminated in a structured manner with less
736 signal blocking. Moreover, our proposed scheme addresses the trade-off between latency and reach-
737 ability in sender-oriented and receiver-oriented mechanisms by exploiting the best features of both
738 mechanisms in one hybrid scheme. To do this, an explicit selection of the relays is adopted as the
739 primary relays selection algorithm, enabling a continues retransmission at the application layer to
740 ensure low dissemination latency. As the explicit selection of relays has a high sensitivity with the
741 frequent disconnection of the link connections in VANETs, an implicit selection of relays is adopted
742 as a recovery strategy to compensate for the lost packets each time a link failure is occurred. In a
743 word, a tight coupling of both sender-oriented and receiver oriented mechanisms is realized in one
744 hybrid scheme to enhance the robustness of the relays selection algorithm.

745 Numerical simulation results reveal that our proposed BACKNET-HSR provides an interesting
746 improvement compared to other typical dissemination protocols under two different simulation
747 scenarios, particularly in terms of information coverage capability and latency. However, it adds
748 some extra overheads depending on the considered road-map topology. The applicability of other
749 relays distribution models without loss of BACKNET-HSR generality is an open issue in our future
750 extension of this work. Meanwhile, it should be noted that BACKNET-HSR's relays distribution
751 model is designed as the first part of a misbehavior reporting scheme with the ability of distributed
752 data merging. BACKNET-HSR will be used to polls the vehicles roaming inside an area of interest
753 to report their own misbehavior analysis. Then, we will exploit the coverage capability of the
754 realized in-road backbones to merge the aggregated reports and backward the results toward the
755 misbehavior authority.

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