

Reliable Emergency Message Dissemination Scheme for Urban Vehicular Networks

Wiem Benrhaïem^{1b}, Abdelhakim Hafid^{1b}, and Pratap Kumar Sahu

Abstract—Vehicular safety applications based on DSRC/802.11p have strict reliability requirement (greater than 0.99). However, it is difficult to achieve high reliability in wireless medium as the transmission is vulnerable to various wave propagation issues. To the best of our knowledge, none of the existing emergency message dissemination schemes in the literature, achieves a predefined reliability in the lossy channel. In this paper, we propose a novel scheme, called reliable emergency message dissemination scheme (REMD), which achieves a predefined reliability for message dissemination while satisfying delay requirements, for various channel conditions. We aim to guarantee very high reliability (e.g., 99%) in each hop, with low control overhead while keeping low end-to-end latency for time-critical applications. We employ zero-correlated unipolar orthogonal codes to combat hidden terminal problem. We exploit periodic beacons, to accurately estimate reception quality of 802.11p wireless link in each cell; then, we use this information to determine the optimal number of broadcast repetitions in each hop. In addition, to ensure reliability in multi-hop, we utilize cooperative communication. The simulation results show that REMD outperforms the existing well-known schemes in the literature. Furthermore, REMD satisfies latency requirements for time-critical vehicular applications and has less network overhead than the existing schemes.

Index Terms—Reliability requirement, multi-hop broadcasting, emergency message, urban vehicular networks, stochastic modeling.

I. INTRODUCTION

THE main objective of Intelligent Transportation System (ITS) is to improve road safety. On detecting an unexpected event (i.e., a traffic accident), a vehicle immediately broadcasts an emergency message to notify nearby related drivers ahead of time to allow them to take action in time [4]. No driver should be deprived of information about emergency events. Consequently, high reliability of message dissemination is required. Indeed, the MAC layer of the DSRC/802.11p standard [19] has strict reliability requirements [20] for safety-related applications (i.e., the probability of message delivery failure should be less than 0.01 [20]). It is also important that the message transfer is completed with the minimum possible delay to give drivers enough time to undertake early

countermeasures [13], [23]. Under such a fact, the delay requirement for many safety-related applications is a lower bound value compared with driver reaction time [13], [31].

Still, one-hop broadcast reliability is not included in the emerging DSRC standard [5], [21], [28], [44]. Indeed, DSRC/802.11p-based broadcast does not support acknowledgement [19], packet retransmission and medium reservation (i.e., RTS/CTS). Many factors can influence probability of successful message reception in wireless communications [18]. Typically, random loss is caused by lossy wireless channel (i.e., signal power attenuation, collision, interference) and node mobility. Safety message broadcast experiences collisions with beacons either due to direct neighbors (i.e., one-hop neighbors) accessing the channel at the same time or due to two-hop neighbors (i.e., the hidden terminal problem [22]). Furthermore, dynamic mobility of vehicles makes reliability of communication in vehicular networks more complex [11]. These effects are quite predominant in urban vehicular networks in the presence of high rise buildings making vehicular networks quite unreliable. Hence, DSRC/802.11p-based broadcast fails to offer reliability.

Several multi-hop broadcast schemes have been proposed in [6]–[8], [24], [36], and [59]. In [6], [7], and [36], the emergency message is forwarded to selective forwarders in quick successions. However, in case the forwarder has moved away or is malfunctioning, the multi-hop communication would not be possible. Other schemes [11], [24], [37], [39] propose techniques to mitigate broadcast storm problem. However, these schemes do not consider MAC layer issues in their forwarding node selection mechanism. Random repetitions schemes like SFR [9] employs random repetition slots to increase the probability of successful message reception [11]. However, SFR [9] results in low reception probability because of hidden terminal problem. Xu *et al.* [9], Torrent-Moreno *et al.* [29], and Zhang *et al.* [38] proposed to compute structured repetitions pattern based on positive orthogonal codes (POC) [56] (AKA unipolar orthogonal codes (UPOC)) in order to time separate interfering nodes. However, a fixed number of repetitions per time unit may result in the transmission of either too few or too many packets. In addition, existing structured repetitions based schemes [9], [29], [38] are not compatible with the CSMA/CA mechanism of DSRC/802.11p [25].

To overcome these limitations, we propose a reliable multi-hop broadcast scheme (REMD). We have already presented a first version of our scheme in [44] and now we present an extended and elaborated version. To the best of our knowledge, this contribution is the first to guarantee a predefined reliability

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The authors are with the Network Research Laboratory, Department of Computer Science and Operation Research, University of Montreal, Montreal, QC H3T 1N8, Canada (e-mail: benrhaiw@iro.umontreal.ca; ahafid@iro.umontreal.ca; pratap.kumar.sahu@gmail.com).

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90 while keeping low end-to-end delay in lossy channel. REMD
 91 allows estimating, with high accuracy, the reception quality
 92 of links in the transmission range. Then, it uses this infor-
 93 mation to determine optimal number of emergency message
 94 repetitions (rebroadcasting) in order to satisfy the predefined
 95 reliability requirement in each hop. REMD combats hidden
 96 terminals using Uni-Polar orthogonal codes (UPOC). REMD
 97 carefully selects multiple forwarders and their positions and
 98 employs cooperative communication to reinforce achieving
 99 high reliability in each hop.

100 The remainder of this paper is organized as follows.
 101 Section II presents related work. Section III presents a brief
 102 overview of REMD. Section IV describes, in details, REMD.
 103 Section V evaluates, via simulations, the performance of
 104 REMD and compares it to existing related schemes. Finally,
 105 Section VI concludes the paper and presents future work.

106 II. RELATED WORK AND MOTIVATION

107 Various multi-hop broadcast schemes have been designed
 108 for vehicular networks. In [39], weighted p-persistence, slot-
 109 ted 1 - persistence, and slotted p-persistence are introduced.
 110 These techniques generate redundant retransmissions in dense
 111 networks resulting in large communication delay. SAPF [24]
 112 regulates the rebroadcast probability adaptively based on
 113 the speed of vehicles. However, the techniques in [39] and
 114 SAPF [24] are not suitable for safety-related applications.
 115 Furthermore, SAPF [24], weighted p-persistence [39], slot-
 116 ted 1-persistence [39] and slotted p-persistence [39] do not
 117 consider MAC layer issues (i.e., the hidden terminal problem,
 118 packet collisions, interference, link unreliability, etc.) [27]
 119 which make forwarders selection unreliable in lossy wireless
 120 channel (i.e., city settings). DBA-MAC [37] and ABSM [11]
 121 disseminate messages based on an already formed virtual
 122 backbone structure [26]. These schemes select backbone nodes
 123 to forward the message to next hop. DBA-MAC [37] selects
 124 backbone nodes based on the estimated lifetime of wireless
 125 connection links. However, DBA-MAC achieves low packet
 126 reception rate in the presence of lossy wireless channel.
 127 ABSM [11] makes use of acknowledgements (beacons include
 128 identifiers of the recently received broadcast messages to serve
 129 as acknowledgments) to enhance reliability. In ABSM [11],
 130 if at least one neighbor does not acknowledge the message,
 131 the backbone node performs more retransmissions. In dense
 132 networks, ABSM [11] performs redundant retransmissions due
 133 to increased packet collisions. Furthermore, creation and main-
 134 tenance of the backbone structure (i.e., links of the backbone
 135 nodes) generates high communication overhead. 3P3B [35],
 136 “Abiding Geocast” [6] and PAB [7] allow the farthest possible
 137 vehicle to perform forwarding. However, the time gap between
 138 beacon sending time of a node and the time at which that node
 139 becomes a forwarder may be very long. In such situations, the
 140 forwarder may not be within the range of the sender. Thus,
 141 the sender remains unaware of message dissemination and
 142 starts rebroadcasting. PMBP [32] selects the farthest forward-
 143 ing node according to its distance to the sender. Similarly,
 144 ROFF [33] selects the farthest node using distance to the
 145 sender. However, one-hop broadcast reception rate is lower

146 in farthest positions due to channel fading [20]. As a result,
 147 ROFF [33], PMBP [32] 3P3B [35], “Abiding Geocast” [6]
 148 and PAB [7] perform multiple timer-based retransmissions
 149 which do not satisfy the delay requirements of safety-related
 150 applications. CLBP [34] selects a single forwarding node
 151 and makes use of BRTS/BCTS packets to prevent hidden
 152 terminal problem. A single BRTS packet is vulnerable to
 153 interference, in city scenarios. To ensure reliable message
 154 delivery to forwarder, the latter sends an acknowledgement
 155 (ACK) frame back to the sender. However, an acknowledge-
 156 ment (ACK) mechanism is generally not robust under harsh
 157 channel conditions. In addition, a single selected forwarding
 158 node may change direction or be malfunctioning. Moreover,
 159 in [6], [7], and [34] intermediate nodes perform overhearing
 160 to receive messages. The overhearing approach does not guar-
 161 antee successful message reception in lossy wireless channel.
 162 Oppcast [10] selects the farthest possible neighboring node
 163 based on acknowledgements (ACK) and retransmissions to
 164 forward the message to next hop. To improve packet reception
 165 ratio for intermediate nodes, Oppcast [10] elects ‘makeups’
 166 (intermediate forwarders). The makeups rebroadcast the mes-
 167 sage to enhance the packet reception rate PRR in each one-
 168 hop area. However, the ‘makeups’ are selected, based on their
 169 distance to the sender. In adverse network conditions, selected
 170 makeups may have low reception quality resulting in packet
 171 loss. Oppcast [10] is more concerned by delay than reliability.
 172 Consequently, emergency messages may be received with low
 173 latency at the cost of lower reliability.

174 Recently, a family of repetition-based MAC proto-
 175 cols [9], [20] has been proposed for the broadcasting of
 176 safety messages in vehicular networks. Each vehicle uses
 177 a repetition-based MAC in order to achieve high reception
 178 success probability. Consider time is divided into frames. Each
 179 frame, in turn, is divided into k time slots with length equals
 180 to the transmission time of a single packet. SPR [9] transmits
 181 the packet in each timeslot in a frame with probability p . In this
 182 approach, a packet may be transmitted L times or not trans-
 183 mitted at all. FR-EMD [40] adjusts the number of repetitions
 184 based on the network density. However, in city settings, what-
 185 ever the number of broadcast repetitions, FR-EMD does not
 186 guarantee high reliability in lossy wireless channel. In POC-
 187 MAC [53], the distribution of repetition patterns to nodes
 188 uses considerable channel resources (i.e., available codes are
 189 acquired through message-passing) in high density networks.
 190 In lossy channel, the exchanged messages (message-passing
 191 between vehicles to update codes availability information) can
 192 be lost. This may result in erroneous code assignment (i.e.,
 193 two neighboring nodes may allocate same code) resulting in
 194 unreliability. CPF [38] extends POC-MAC [53] for multi-
 195 hop emergency message dissemination in highway scenarios.
 196 In lossy wireless channel, selected forwarders may have bad
 197 link reception quality resulting in failed reception. As a result,
 198 CPF [38] does not guarantee high broadcast reliability in
 199 lossy channel. Indeed, if fixed number of message repetitions
 200 is forwarded over a frame, they may be sending either too
 201 few or too many packets. In addition, structured repetition-
 202 based schemes [38], [53] are not compatible with emerging
 203 DSRC/802.11p [6].

204 In this paper, REMD provides a solution to existing
 205 reliability issues. More specifically, REMD allows estimat-
 206 ing/predicting, with high accuracy, the link reception quality.
 207 Then, it uses this information in order to guarantee:

- 208 1) One hop reliability of 802.11p-based broadcast:
 - 209 • By carrying out an optimal number of emergency
 - 210 message repetitions. Repetition patterns are com-
 211 puted based on Uni-polar orthogonal codes (UPOC)
 212 to combat hidden terminal problem.
- 213 2) Multi-hop reliability:
 - 214 • By carefully selecting multiple forwarders and their
 - 215 positions, each single hop; and
 - 216 • By employing a cooperative communication scheme
 217 that allows forwarders to retransmit the emergency
 218 message an optimal number of times with the objec-
 219 tive of ensuring high retransmission reliability.

220 III. RELIABLE EMERGENCY MESSAGE DISSEMINATION: 221 AN OVERVIEW

222 REMD is designed to disseminate emergency messages
 223 with very high reliability in urban vehicular network. The
 224 main idea of REMD is to guarantee broadcast reliability (e.g.,
 225 $r_{th} = 99\%$) [20] at each hop by performing an optimal
 226 number of broadcast repetitions. Basically, REMD estimates,
 227 with high accuracy, the reception quality of wireless link in
 228 the transmission range Tr : Then, it uses this information to
 229 compute an optimal number of message repetitions and to
 230 select multiple forwarders and their positions at each hop. The
 231 forwarders of each hop perform cooperative communication to
 232 reinforce achieving high reliability.

233 A. Assumptions

234 We assume that (a) vehicles are moving on urban streets;
 235 a scenario where a source node with a generic emergency
 236 message M that requires multi-hop transmission is intended
 237 for all nearby vehicles in a geographical area; (b) vehicles are
 238 equipped with Global Positioning System (GPS) and digital
 239 road maps; (c) vehicles are equipped with IEEE 802.11p [2]
 240 wireless technology and computation capabilities; (d) obsta-
 241 cles (e.g., buildings, moving vehicles) exist; they impact
 242 communication among vehicles; and (e) the factors causing
 243 failures of message transmissions are temporary or intermittent
 244 (e.g., failure of 802.11p/GPS in a vehicle is not considered).

245 B. Network Model and Definitions

246 In the following, we present the definitions of the relevant
 247 terms used to describe REMD.

- 248 • **Source node:** It defines the vehicle that detects an
 249 unexpected event.
- 250 • **Target area:** It defines the geographical area that includes
 251 all vehicles approaching/driving, towards the source, that
 252 are intended recipients of the emergency message gener-
 253 ated by the source node.
- 254 • **Segment:** It defines the area between two road
 255 intersections.

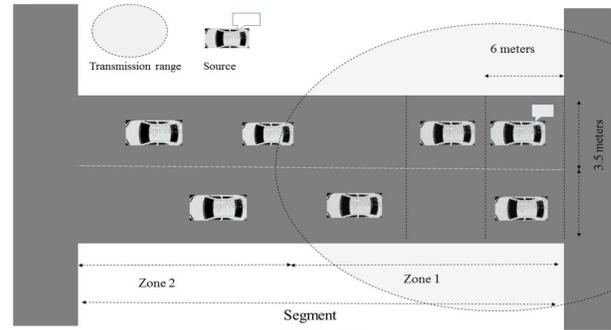


Fig. 1. Target area structure.

- 256 • **Zone:** It defines a static portion of the segment whose
 257 length is same as the transmission range of a vehicle.
 258 Based on its length, a road segment is divided into a
 259 number of zones.
- 260 • **Cell:** It defines a static partition of a zone with predefined
 261 length (e.g., length of a Car $y = \sim 6$ m [46]). A
 262 cell represents a possible vehicle position (a fine-grain local-
 263 ization of vehicles). Assuming the lowest speed in the
 264 city is equal to 10 km/h, the minimum distance between
 265 two vehicles is $\frac{10000 \times 2}{3600} \cong 5.55$ m. Thus, there will be
 266 either 1 vehicle or no vehicle in each cell. In each zone,
 267 cells are identified/numbered 1, 2, 3, etc.
- 268 • **Transit time:** It defines the time interval that a vehicle
 269 takes to transit a cell (a vehicle position). If V is the
 270 vehicle velocity, the transit delay T_s is computed as
 271 follows:

$$272 T_s = \frac{6}{V} \quad (1)$$
- 273 • **Regular vehicle:** It defines a passing vehicle. During T_s ,
 274 such a vehicle records cell information. Then, it includes
 275 this information in its next beacon. We use the term
 276 regular vehicle or vehicle interchangeably to denote a
 277 passing vehicle.
- 278 • **Coordinator:** It defines a vehicle, located around the
 279 center of a zone, which continuously processes received
 280 beacons of vehicles in the effective zone (i.e., the current
 281 zone). There exists a coordinator per zone.
- 282 • **Coordination packet (CP):** It defines a periodic packet
 283 transmitted by the coordinator. The coordinator transmits
 284 periodic CPs instead of periodic beacons (See Fig. 1). CP
 285 includes the status information of the coordinator (posi-
 286 tion, velocity, direction, etc.) together with information it
 287 processed. The transmission power of CP is two times
 288 the beacon's one.
- 289 • **Sender:** It defines the current broadcast node (a node that
 290 intends to transmit the emergency message). The source is
 291 a sender when it first broadcasts the emergency message.

292 C. REMD Components

293 The objective of REMD is to determine an optimal number
 294 of message repetitions and forwarders, together with their
 295 positions, to achieve reliability requirements. It consists of an
 296 initialization phase, called IN, and 5 key phases: (a) Data Col-
 297 lection (DC); (b) Local State Processing (LSP); (c) Broadcast

Reliability guarantee (BR); (d) Forwarders Selection (FS); and (e) Cooperative one-hop reliability guarantee (C-reliability). IN is executed once to assign a zero-correlated Uni-Polar orthogonal code to each zone. DC and LSP run continuously whereas BR, FS and C-reliability run only when an event requiring a message to be disseminated to vehicles in a target area occurs. It is important to note that REMD is also applicable for safety applications that rely on one-hop message broadcast. In that context, FS and C-reliability phases are omitted.

(a) DC: It is executed by regular vehicles; more specifically, a regular vehicle records its state information (i.e. packet collision rate and average signal power attenuation). Then, it includes this information in its periodic beacons. The objective of this phase is to provide the coordinator with information about wireless channel state in its effective zone.

(b) LSP: The coordinator executes LSP to process beacons received from neighboring vehicles, to estimate/predict link reception quality of 802.11p wireless link of vehicles in each zone; then, it includes this information in next CP.

(c) BR: It is executed at the source and at the forwarders. Using recent received CPs, the source (or the forwarder) computes optimal number of broadcast repetitions that satisfy reliability requirements in its transmission range.

(d) FS: It is executed at the source and at a specific forwarder. Using recent received CPs, the source (or the forwarder) selects multiple forwarding nodes and their positions in its transmission range.

(e) C-Reliability: The forwarders of same hop execute C-reliability, in a distributed fashion, and coordinate to select next-hop relays (forwarders). More specifically, the forwarders perform cooperative communication to send/repeat the emergency message an optimal number of times with the objective to ensure high reliability in next hop.

IV. RELIABLE EMERGENCY MESSAGE DISSEMINATION: A DETAILED DESCRIPTION

In the following we describe the details of the six phases of REMD.

A. Initialization (IN)

To combat hidden terminal problem, REMD assigns to each zone a specific code (repetition pattern) obtained from zero-correlated Uni-Polar orthogonal codes in order to time-separate interfering nodes. Let $\zeta = (L, \varpi, \lambda)$ be a set of UPOCs, where L is the code length, ϖ is the code weight and λ is the cross-correlation [56]. Let $x = (x_1, x_2, \dots, x_L) \in \zeta$ and $y = (y_1, y_2, \dots, y_L) \in \zeta$ be two codes such that $x \neq y$. Let τ ($1 \leq \tau \leq L - 1$) be a circular displacement. The cross-correlation property is defined as follows: $\sum_0^{L-1} x_i * y_{i \oplus \tau} \leq \lambda$.

A repetition pattern represents a binary sequence of length L in which bit 1 denotes a transmission and bit 0 represents an idle timeslot. In each timeslot, if a node is not transmitting, it switches to the idle mode. The code assignment scheme must ensure that the cross-correlation property λ ($0 \leq \lambda \leq \varpi - 1$) with 2-hop neighboring nodes is zero. The average segment

length is smaller or equal to 500 m [58]. In the model of city roads network used in this work, the average road segment length is double the transmission range (transmission range is 250 m [12]). Hence, a node along a road segment can interfere with up to 4 other nodes along adjacent road segments (2 nodes in two zones on the same road and 2 nodes in two zones along the perpendicular roads). Thus, at least 5 codes (i.e., $|\zeta| = 5$) having zero correlation are required. Chung and Yang [3] provide an upper bound for the size of codes $|\zeta| = \lfloor \frac{L}{\varpi} \rfloor$, where L is the code length and ϖ is the code weight.

B. Data Collection (DC)

DC allows collecting packet loss rate (PL) and signal power attenuation rate (PA). DC is executed at regular vehicles. During the transit delay T_s , a vehicle transiting a cell may receive multiple packets. At the end of T_s , the vehicle computes PL (see (2)) and PA (see (3)) for that cell. The packet loss rate of cell x at time t is given as follows:

$$PL(x, t) = \frac{NL}{Nt} \quad (2)$$

where Nt is the total number of packets and NL is the number of lost packets. To compute PL, we assume that (a) The number of packets resulting from 3 or more packets colliding at any instant t is negligible [41]; and (b) The number of packets that fail to be detected by the receiver's radio device is negligible [42]. Therefore, the number of lost packets NL detected by vehicle v , during T_s , is equal to the sum of the number of non-decodable messages, n_1 , from senders located in the interference range of v and the number of collisions, n_2 , due to "real" collisions of packets emitted from two senders that are both in range of the receiver (i.e., $NL = n_1 + 2 \times n_2$). Using (2) requires that the vehicle determines the "real" number of packets Nt sent by nodes in range or in interference range; the "real" number of packets includes packets that did not reach the vehicle; in practice, a receiver is unable to record such information. The "real" number of packets Nt is equal to the sum of the number of lost packets NL and the number of successfully received packets Nr (i.e., $Nt = NL + Nr$). The signal power attenuation rate PA of cell x at time t is expressed as follows:

$$PA(x, t) = \frac{1}{Nr} * \sum_{i=1}^{i=Nr} \left(\frac{X_0(d_i)}{Tx} \right) \quad (3)$$

where d_i is the distance to neighbor i , $X_0(d_i)$ is the power attenuation rate of a packet sent by neighbor i , and Tx is the transmitted signal power. Upon a successful reception of a packet, the vehicle records the packet's received signal strength indicator (RSSI) and its transmitted power Tx . It is worth noting that signal power attenuation, reception power and transmitted power are only available for successfully received packets. In a realistic channel model, like Rayleigh, the $RSSI$ value at distance d from the transmitter is given by:

$$RSSI(d) = Tx - Los(d_0) - 10 * \rho * \log_{10} \left(\frac{d}{d_0} \right) + X_0 \quad (4)$$

where Tx is the transmitted power in decibel (DB), $Los(d_0)$ is the path loss at a reference distance (i.e., d_0), ρ is the path loss exponent and X_0 denotes the signal attenuation in decibel. X_0 is modeled as a random variable with Rayleigh distribution [43]. The value of ρ can be set depending on the propagation environment [43]. Our objective is to extract the value of the attenuation effect X_0 from the received RSSI value. To achieve this, we consider one sender and one receiver, spaced by m meters. The transmitter emits only one packet to be exposed to only fading and path loss effect (i.e., $X_0 = 0$). In this case, the receiver records signal power degradation ($Tx - RSSI$). Then, it calculates the average attenuation per meter (e.g., for $d = 20$ m and 0.08 db; we obtain signal power degradation rate $\alpha \approx 0.004$ db/m). Thus, the receiver is able to extract X_0 from RSSI (i.e., $X_0(d) = RSSI(d) - \alpha * d$). At the end of T , regular vehicle includes PL and PA in its next beacon.

C. Local State Processing (LSP)

This phase estimates link reception quality Q in the transmission range. LSP is executed at the coordinator node. The coordinator acts as a zone manager. It is in charge of processing exchanged beacons. Indeed, the zone manager provides a source node with data corresponding to its range. A coordinator is chosen dynamically through exchange of beacons. To select a coordinator, we introduce a status flag in beacons, which, if set, represents a coordinator vehicle; otherwise, it represents a regular vehicle. We define the start coordination position S_p as one-quarter of the transmission range away from the beginning of the zone and the last coordination position L_p as three-quarter of the transmission range away from the beginning of the zone. If a vehicle finds itself as the closest vehicle to the position S_p , it sets its status to coordinator; a flag is included in periodic beacons to represent the status of a vehicle (i.e., coordinator or regular vehicle). Upon reaching the position L_p , it resets its status (i.e., becomes regular vehicle) and allows another vehicle located in S_p (or nearby) to be the zone manager. At any time, there is only one coordinator per zone. Upon receipt of a beacon from a vehicle located in cell x at time t , the coordinator extracts: (a) $PL(x, t)$ to measure the quality of wireless link in cell x (see (5)); and (b) $PA(x, t)$ to compute an equivalent packet loss rate $ePL(x, t)$ (see (6)). Let us analyze the variation, over time, of average attenuation (PA) and packet loss rate (PR) for cell 'A' (see Fig. 4). By using 4th order polynomial curve fitting [45], we show that PA and PL have similar variations (see Fig. 4); they have linear correlation. We extract the conversion ratio μ (correlation coefficient) that represents the average attenuation to the average packet loss over a period of time. Therefore, the reception quality of 802.11p wireless link $Q(x, t)$ at time t can be expressed as follows:

$$Q(x, t) = 1 - PL(x, t) \quad (5)$$

In case of controlled channel condition, reported PL values may be equal to zero. Therefore, the reception quality of 802.11p wireless link $Q(x, t)$ at time t can be expressed

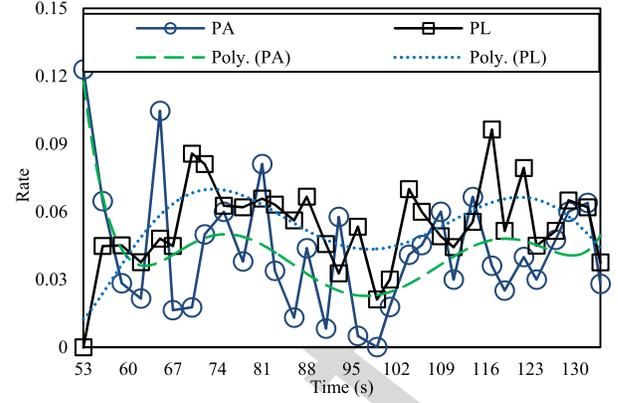


Fig. 2. Distribution of PA and PL over time in a cell.

as follows:

$$Q(x, t) = 1 - ePL(x, t) = 1 - \mu * PA(x, t) \quad (6)$$

Link reception quality $Q(x, t)$ changes over time due to the dynamic nature of vehicular networks; thus, if the source node uses reception quality measured at t_1 by the coordinator, to execute actions at t_2 ($t_2 > t_1$), wrongful decisions may be taken (e.g., selection of forwarders). Thus, before transmission of CP at t_2 , the coordinator estimates/predicts, with high accuracy, link quality at t_2 based on its quality history (i.e., quality at t_1 and earlier). The coordinator makes use of PA and PL, previously measured (see Fig. 2) in its neighboring cells (i.e., in its transmission range), to predict future values of PA and PL, with high accuracy. For prediction, it extends the historical time-series PL and PA to future periods using curve-fitting.

To achieve this, let us do a polynomial modeling of PL and PA values for a cell A . Let $P(t)$ and $R(t)$ denote k^{th} order polynomials that represent PL-trend and PA-trend, respectively. $P(t)$ and $R(t)$ are defined as follows:

$$P(t) = a_0 + a_1t + a_2t^2 + \dots + a_kt^k \quad (7)$$

$$R(t) = b_0 + b_1t + b_2t^2 + \dots + b_kt^k \quad (8)$$

The problem of determining $P(t)$ is reduced to that of determining the coefficients a_i , where $0 \leq i \leq k$, as accurately as possible using experimental results and taking into account experimental errors. Quantifying the error for the polynomial trend using the least squares approach is as follows:

$$err = \sum (d_i)^2 = \sum (PL(t_i) - P(t_i))^2 \quad (9)$$

Note that it is particularly difficult to accurately estimate/predict the channel condition in vehicular networks due to the frequently changing network environment [47]. Although there are some limitations for the polynomial modeling based estimation, we can minimize the error in (9). Similarly, coefficients in (8) can be estimated. The approximation of PL and PA variations are then $P(t)$ and $Q(t)$. Therefore, the coordinator sets a local state map (LSM), and includes it in its next CP. LSM consists of link reception quality $Q(x, t)$ of vehicles in its effective zone.

493 D. Broadcast Reliability (BR)

494 This phase allows guaranteeing predefined reliability r_{th} in
495 transmission range. To achieve this, the vehicle rapidly repeats
496 the message an optimal number of times, using the repetition
497 pattern of its effective zone, with the objective to enhance
498 reception probability per-receiver. More specifically, we con-
499 sider a useful message lifetime T whose value is smaller
500 than human reaction time; the vehicle repeats broadcasting the
501 packet multiple times only within T . Let α be the time needed
502 to perform one repetition ($\tau = 1$ time slot). The transmitter
503 evenly splits the lifetime into L time slots, where $L = \lfloor \frac{T}{\alpha} \rfloor$.
504 L represents also the code length (maximum number of codes
505 needed to time-separate interfering nodes). Each repetition of
506 the message is a new packet. The cell transit time T_s ranges
507 between 0.2 s and 0.4 s while the message lifetime T is less
508 than 0.5 s. Link reception quality $Q(x, t)$ represents reception
509 probability $p(x)$ per slot. $p(x)$ is expressed as follows:

$$510 \quad p(x) = Q(x, t) \quad (10)$$

511 During T , the sender performs n repetitions. Excessive rep-
512 etitions might cause congestion leading to collisions [52].
513 Therefore, an optimal number of repetitions n_{opt} must be
514 determined. Let N_g be the number of neighbors in trans-
515 mission range, $t_k (1 \leq k \leq L)$ be a random variable that
516 indicates that k time slots are picked (i.e., k repetitions are
517 performed) and $X_i (0 \leq i \leq N_g)$ be a random variable
518 taking values 0 and 1. X_i follows a Bernoulli random variable
519 $X_i \sim \beta(p(x))$ with success probability p_i , associated with
520 receiver i . The probability mass function (p.m.f) of X_i is
521 expressed in (11). Let Y_i^k be a geometric random variable
522 $Y_i^k \sim \text{geo}(p(x))$ associated with receiver i , ($1 \leq i \leq N_g$). The
523 geometric random variable Y_i^k returns the number of Bernoulli
524 trials (repetitions) as expressed in (12). Probability of first
525 success at the k^{th} repetition, for $k \geq 1$, is given in (13).

$$526 \quad p(X_i = 1) = p_i = Q(x, t) = 1 - p(X_i = 0) \quad (11)$$

$$527 \quad Y_i^k = k \iff (X_i^1 = 0, X_i^2 = 0, \dots, X_i^{k-1} = 0, X_i^k = 1) \quad (12)$$

$$528 \quad P(Y_i = k) = p_i * (1 - p_i)^{k-1} \quad (13)$$

529 The integer linear programming (ILP) [57] of the broadcast
530 reliability (BR) problem can be expressed as follows:

$$531 \quad \text{Max}_{1 \leq i \leq N_g} \left(\text{Min}_{1 \leq k \leq L} \left(Y_i^k * t_k \right) \right) \quad (14)$$

532 *S.t.*

$$533 \quad \frac{1}{N} * \sum_{k=1}^{k=L} \left(\sum_{i=1}^{i=N_g} \left(X_i^k * t_k \right) \right) \geq r_{th} \quad (15)$$

$$534 \quad t_k, X_i^k \in \{0, 1\} \quad \text{for all } i, k \quad (16)$$

535 The objective function (14) maximizes the minimum number
536 of repetitions. Constraint (15) guarantees broadcast reliability
537 requirement r_{th} . We define the broadcast reliability metric as
538 the ratio of the number of vehicles, in the transmission range,
539 that successfully receive the message within its lifetime T ,
540 to the number of total neighbors. This metric is called packet
541 reception rate (PRR). PRR is the common deterministic metric

to measure one-hop broadcast reliability protocols [1]. Hence,
constraint (15) can be written as follows:

$$542 \quad \text{PRR} \geq r_{th} \quad (17) \quad 544$$

545 Constraint (16) is the integrity constraint of the decision
546 variables. BR is a linear MaxMin problem [49]; we solve this
547 problem using an iterative procedure. The main idea of the
548 solution is to increment repetitions by 1 and compute PRR.
549 The number of repetitions (Eq.(14)) achieves its minimum
550 value n_{opt} the first time PRR becomes greater than the
551 predefined reliability threshold r_{th} . We quantify PRR before
552 a message transmission occurs. In the first repetition, let
553 us suppose Bernoulli random variables $X_i (1 \leq i \leq N_g)$ are
554 independent such that $p_i (1 \leq i \leq N_g)$ are not all identical. Let
555 $S = \sum_{i=1}^{i=N_g} X_i$ be the distribution of their sum. The distribution
556 of S is known to be a Poisson Binomial Distribution [51]. The
557 number of successful receivers is k out of N_g . The probability
558 of having $k (1 \leq k \leq N_g)$ successful receivers out of a total of
559 N_g can be expressed as the following probability mass function
560 (p.m.f) [48]:

$$561 \quad P(S = k) = \sum_{A \in \binom{N_g}{k}} \prod_{i \in A} p_i * \prod_{j \in A^c} (1 - p_j) \quad (18)$$

562 where A^c is the complement of A . In a sequence of n independ-
563 ent repetitions each of success probability $p(x)$, we redefine
564 the Bernoulli random variable X_i , associated with receiver i ,
565 that takes the value one if at least one successful packet
566 reception occurs. Success probability $p_n(x)$ is defined as
567 follows:

$$568 \quad p_n(x) = 1 - (1 - Q(x, t))^n \quad (19)$$

$$569 \quad p_n(x) > Q(x, t) \quad (20)$$

570 The number of trials remains N_g . The probability mass func-
571 tion (p.m.f) of the number of receivers can be reformulated as
572 follows:

$$573 \quad P(S = k) = \sum_{A \in \binom{N_g}{k}} \prod_{i \in A} [1 - (1 - Q(x, t))^n] \quad (21) \quad 574$$

$$* \prod_{j \in A^c} (1 - Q(x, t))^n$$

575 In practice, the sum over $\binom{N_g}{k}$ in (21) has a high com-
576 putational time and space requirements. For example, for
577 $N_g = 40$, the sum generates more than 10^{30} elements. Several
578 solutions have been proposed to calculate probabilities in (21).
579 Le Cam theorem [50] establishes two basic hypothesis for
580 Poisson approximation to the Poisson binomial distribution in
581 the Poisson limit theorem [50]. If $p_i \rightarrow 0$ and $N_g \rightarrow +\infty$,
582 the mean value $\lambda = p_i * N_g$ remains constant. Therefore,
583 $p(S = k)$ in (21) equals to $e^{-\lambda} \frac{\lambda^k}{k!}$. However, we cannot
584 apply Le Cam theorem in vehicular networks since, in this
585 case, $p_i \rightarrow 0$ and $N_g \rightarrow \infty$; indeed, applying Poisson
586 approximation to solve (21) will result in less accurate results.

Thus, we turn to find the exact poisson binomial distribution. To compute the probability mass function (p.m.f) in (21), we make use of Fast Fourier Transform (FFT) based algorithm [54] to speed up the computation. More specifically, we adapt the algorithm in [30] to derive a simplified exact formula of (21). The adapted algorithm is labeled PMF-FFT. Basically, PMB-FFT makes use of the characteristic function of the random variable $S = X_1 + X_2 + \dots + X_n$ to derive Inverse Discrete Fourier Transform (IDFT) equation of the sequence $\{p(s=1), p(s=2) \dots p(s=N_g)\}$. Then, PMB-FFT applies the FFT algorithm [54] to both sides of the derived IDFT equation to get (p.m.f) of the random variable S . The complex part of our proposal is in computing FFT. Or, the time complexity of FFT (and hence of PMF-FFT) is $(N_g \times \log(N_g))$ [54]. We tested our approach using a Laptop (HP) which has 8 GB of RAM and 2.4 GHz of processor speed. The obtained time complexity is in order of microsecond. We expect even much smaller values with more processing power. Let ω_n define the resulting vector of PMF-FFT for the n^{th} repetition. Hence, ω_n represents the exact distribution of poisson binomial distribution. The number of successful receivers k corresponds to the maximum value $\hat{\delta}$, $1 \leq \hat{\delta} \leq N_g$, starting from which the cumulative sum of probability mass function (p.m.f) equals to 0.99. By this way, the number of successful receivers k is obtained with a 99% guarantee. This value is easily obtained using (22). Packet reception rate (PRR) is expressed in (23). The number of repetitions achieves its minimum value n_{opt} the first time PRR becomes greater than the predefined reliability threshold r_{th} ($PRR(n) \geq r_{th}$).

$$\hat{\delta}(n) = \left\{ \max_{1 \leq x \leq N_g} (x); \left(\sum_{k=x}^{N_g} (\omega_n(k)) \right) \geq 0.99 \right\} \quad (22)$$

$$PRR(n) = \frac{\hat{\delta}(n)}{N_g} \quad (23)$$

A vehicle joining a road segment gets the repetition pattern of its effective zone by using the road ID (In a numerical map, each road segment is given a road ID) and its position. Once an event occurs, the vehicle computes its optimal number of repetitions n_{opt} . Then, it maps this number to the repetition pattern of its effective zone (i.e., the vehicle selects first n_{opt} transmission slots out of ϖ). To perform n_{opt} repetitions, we design an overlay, called MAC Repetition Layer (MRL), on the standard MAC Carrier Sensing [55]. MRL is responsible for generating broadcast repetitions. MRL resides between standard MAC layer and Logical Link Control (LLC) layer. The state machine of MRL is shown in Fig. 3. MRL consists of 3 states: (a) *Repeat*; (b) *Drop*; and (c) *Idle*. If a packet is received from LLC layer, MRL switches from *Idle* to *Repeat*. Here, MRL generates n_{opt} packets, associates them to the first n_{opt} ($1 \leq n_{opt} \leq L$) time slots (FIFO) of the repetition pattern and transmits them to the MAC layer; then, it goes back to *Idle*. In case a packet is received from MAC, MRL switches from *Idle* to *Discard*. Here, MRL checks whether the packet is new. If yes, the packet is transmitted to LLC; otherwise, it is discarded.

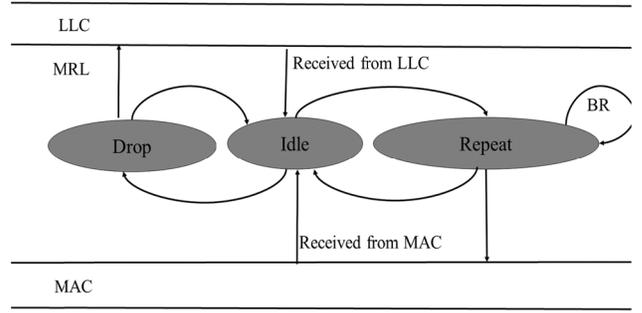


Fig. 3. State machine of MAC Repetitions Layer (MRL).

E. Forwarders Selection (FS)

To relay the message to next hop, REMD executes FS. The main idea of FS is to select multiple next-hop forwarders having best link reception quality $Q(x, t)$. Let n_F be the number of forwarders. Multiple forwarders allow avoiding single forwarder limitations; if only one vehicle is chosen as a forwarder and if that vehicle malfunctions or moves away (i.e., leaves the road segment) the message dissemination will be stopped. For simplification, we take number of repetitions n_{opt} as a reasonable value for n_F . To ensure successful message reception, forwarders should have high success reception probability. Furthermore, it is a known fact that forwarders locations should be close to the border in order to reduce multi-hop latency. FS consists of two steps: (a) Reception-based selection; and (b) Position-based selection.

1) *Reception Based Selection*: The sender makes use of link reception quality information to select forwarders. Forwarders having good link reception quality are better choice to successfully receive the message and retransmit it. Consider neighbors' information is available (i.e., using exchanged beacons). Let v^{N_g} denotes the set of cells in transmission range having vehicles. For each $x \in v^{N_g}$, the sender extracts the corresponding link reception quality $Q(x, t)$, $1 \leq x \leq N_g$, from the most recent CP and picks the best n_F elements of v^{N_g} (in terms of link quality); then, it creates a set v^q that includes these elements ordered from best to worst (in terms of link quality).

2) *Position Based Selection*: In order to reduce hop count, the sender ensures that the forwarders locations are close to the border. To achieve this, for each location $x \in v^q$, the sender makes use of a location shifting technique $\tau(x)$ that moves x to the closest location y to the border while preserving an equivalent link reception quality. In practice, the sender sets up, for each cell, $x \in v^q$, a relative 2D coordinate system $\{X, Y\}$ having the origin x . The X-axis corresponds to reception quality values. The Y-axis corresponds to cells in transmission range. Let $D(x, y)$ define a distance function, on X-axis, such that $D(x, y) = |Q(x, t) - Q(y, t)|$. Let $C(x, y)$ define a distance function, on Y-axis, such that $C(x, y) = |x - y|$. Let $t_{D(\vec{x}, y)}$ define a translation operation on X-axis.

$$x \mapsto t_{D(\vec{x}, y)}(x) = \begin{cases} y & \text{if } \|D(\vec{x}, y)\| \leq L_{th} \\ x & \text{else} \end{cases} \quad (24)$$

$$t_{x,\bar{y}} : v^q \longrightarrow v^{\bar{q}} \quad (25)$$

$$t_{x,\bar{y}} = \begin{cases} y & \text{if } y \geq x \wedge \max_y (C(x, y)), \\ x & \text{else} \end{cases}$$

Specifically, the translation operation $t_{x,\bar{y}}$ assigns to the cell $x \in v^q$ the cell y such that y is the closest cell to the border. Finally, the distance shifting technique $\tau(x)$ combines (24) and (25) in order to obtain the final forwarders locations $\tau(x)$ defined as follows:

$$\tau(x) = t_{x,\bar{0}}(x) = y$$

$$\Leftrightarrow ((|x - y|) \wedge (\|D(\vec{x}, y)\| \leq L_{th}) \wedge (y \geq x)) \quad (26)$$

Let v^F denote the set of resulting forwarders locations. The sender applies a prioritization rule φ_i ($1 \leq i \leq n_F$) to forwarders locations in v^F . The priorities φ_i are specified in (27).

$$\varphi_i = \varphi(v^F(i)) = i \quad (27)$$

The locations of forwarders and their priorities φ_i are included in the emergency message. Such an information is useful to coordinate among forwarders in the C-reliability phase. Specifically, the translation operation $t_{D(\vec{x}, y)}(x)$ assigns to cell $x \in v^q$ a cell $y \in v^{\bar{q}}$ having an equivalent link reception quality ($\|D(\vec{x}, y)\| \leq L_{th}$). In practice, the value of L_{th} is set to 0.01 because we are not able to achieve 100% equivalency. Let $t_{x,\bar{y}}$ define a translation operation on Y-axis.

3) *C-Reliability*: This phase is executed by forwarders of same hop. The forwarders cooperatively perform optimal broadcast repetitions with the objective to reinforce achieving high broadcast reliability. In addition, the forwarders coordinate to select next-hop forwarders. To achieve this, the forwarders take the role of broadcasting the message iteratively with respect to their priorities φ_i . Fig. 4 shows the state machine of C-Reliability phase. Each forwarder j ($1 \leq j \leq n_F$) is assigned a broadcasting timer $T_{ac}(j)$ and its initial value is indicated in (28). If the broadcasting timer expires, corresponding forwarder j performs $n_{re}(j)$ repetitions; initial number of repetitions is indicated in (30). Otherwise, the corresponding forwarder is suspended and the value of its broadcasting timer is updated using (29). Similarly, forwarders update number of repetitions using (31). Initially, the highest priority forwarder (with φ_i) executes broadcast repetitions (BR) and selects next-hop forwarders while forwarders at lower priorities are suspended. Lower priority forwarders overhear message transmissions and record failed receptions as specified in (32) as long as their broadcasting timer is not expired. Indeed, the repetitions are either successfully transmitted or lost before broadcasting timer of forwarder j expires. If broadcasting timer $T_{ac}(j)$ of forwarder j expires, we distinguish three cases: (a) Case 1: Current forwarder j failed to receive all repetitions of higher priority forwarder(s) ($n_{re}(j) = n_{opt}$). This means that higher priority forwarders are malfunctioning or have moved away. Thus, current forwarder j executes forwarders selection (FS) before broadcasting the repetitions; (b) Case 2: Current forwarder

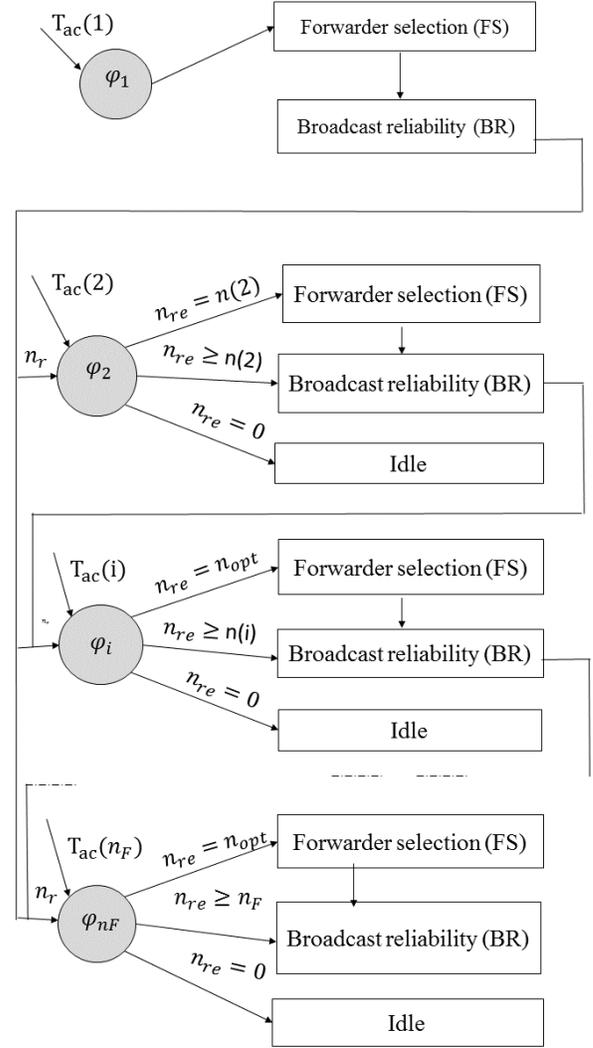


Fig. 4. State machine diagram of Cooperative reliability.

j successfully received all repetitions of higher priority forwarders ($n_{re}(j) = 0$). In this case, current forwarder j remains in idle state and suspends its broadcasting timer; (c) Case 3: Current forwarder j didn't receive successfully all repetitions of higher-priority forwarders ($n_F > n_{re}(j) > 0$). This situation usually occurs when higher-priority forwarders leave the transmission range before accomplishing n_{opt} repetitions. Thus, current forwarder j extracts next-hop forwarders list from the already successfully received repetitions and carries out the rest of repetitions as specified in (31). As long as (33) is not verified, the reliability requirement in current hop is not achieved and the coordination process among forwarders continues.

$$T_{ac}(j) = T_{FS} + n_{opt} * T_{Data}. \quad (28)$$

$$T_{ac}(j) = (j - 1) * \Delta s_j + n_{re}(j) * T_{Data}. \quad (29)$$

$$n_{re}(j) = n_{opt}. \quad (30)$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Fading model	Rayleigh, Nakagami
Transmission range (T_r)	250 m [14]
WM, Beacon, CP length	292,72, 120 bytes.
Vehicle density	~40-120 vehicals /km
Reliability requirement r_{th}	0.99
Simulation duration	150 seconds
Coordinator CP rate, Beacon rate	10 packets/s
Vehicle speed V	30-50 km/hour
Message generation rate	4-5 messages/s

$$n_{re}(j) = n_{opt} - \left(\sum_{i=3}^{i=j} (n_{opt} - n_{re}(i-1)) \right). \quad (31)$$

$$n_{re}(j) = n_{re}(j) + 1. \quad (32)$$

$$n_{opt} = \left(\sum_{i=1}^{i=j} n_{re}(i) \right). \quad (33)$$

V. SIMULATIONS

In this section, we present a simulation-based evaluation of REMD and 4 other data dissemination schemes, i.e., ABSM [11], 3P3B [35], Oppcast [10] and CPF [38]. While [10] and [11] are based on CSMA and propose techniques to improve reliability in multi-hop including intermediate nodes reachability, CFP is a recent repetition-based MAC scheme that uses structured repetitions. We chose also [35] as it is a recent emergency message dissemination scheme.

A. Experiment Setup

We run simulations using Omnet ++ 4.3 [15] as a discrete event simulator and Sumo traffic simulator [17]. Our C ++ code uses Veins 2.2.1 [16] for DSRC simulated components [16]. We configured Omnet ++ to model the impact of both distance and obstacles (i.e., buildings and moving vehicles) on the signal propagation. In our work, we choose the Rayleigh propagation model and Nakagami-m propagation model to test REMD in a more realistic fading environment. The value of the m parameter, also called shape factor, indicates the severity of multipath fading, and is a measure of channel quality. The Nakagami-m distribution models multipath fading conditions that are more severe than Rayleigh fading. When $m = 1$, the Nakagami-m distribution becomes the Rayleigh distribution. To increase fading effects, Nakagami uses smaller values for m. This makes it possible to model intensely faded channels (due to obstacles). Table I shows the simulation parameters. The specific parameters for 802.11p protocol are set in the 'omnetpp.ini' file of Omnet ++ simulator. We consider a real city map composed of a real city street map (www.openstreetmap.org/). The map has a grid-like city model. The map has intersections. In the chosen real street map based model, the average length of a road segment is 250 meters. Each road segment contains two lanes. The total length of the city streets segments is 3.5 km

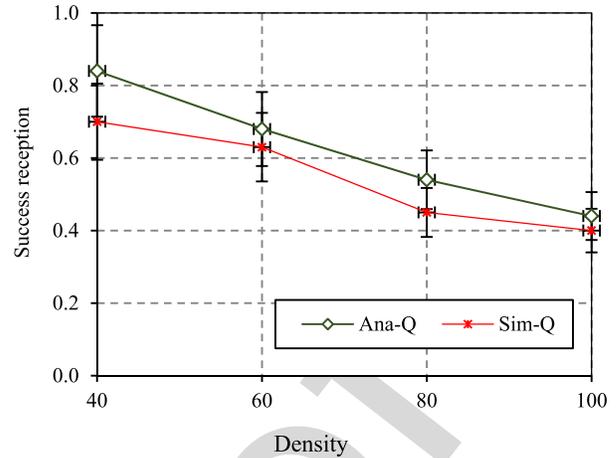


Fig. 5. Link quality vs. Density.

in an area of 1.5 km \times 2.25 km. We consider the following simulation scenario: a set of vehicles distributed uniformly on road segments (1 vehicle/lane/250meter) act as message sources. The scenario consists of 300 cars (nodes) on 20 street segments. During simulation, the source vehicles broadcast generic emergency messages at a rate of r messages/s. Simulation results, averaged over 50 runs; they are characterized by a 94% confidence interval. The performance parameters, we consider in the evaluation of REMD, are: (a) packet reception ratio (PRR)(%): The percentage of vehicles that receive the disseminated message; (b) Average propagation delay (ms): The average length of time between the time a message is transmitted by the source and the time it is received by the vehicles in the target area; and (c) Network load ($Bytes/road\ segment$): the amount of traffic in terms of beacons, emergency messages and their retransmissions.

B. Validation

The objective of this section is to validate the analytical findings of REMD using Omnet ++ simulations. More specifically, we validate the followings: (a) link reception quality $Q(x, t)$ (see (5)-(6)); (b) packet reception rate PRR (see (23)); and (c) optimal number of repetitions n_{opt} (see (14)).

Fig. 5 shows reception quality $Q(x, t)$ plotted against vehicle density. As expected, $Q(x, t)$ decreases when vehicle density increases. This is expected since the traffic of periodic beacons increases with density. This observation validates the use of $Q(x, t)$ to assess 802.11p reception quality in cells. The analytical results closely follow simulation results especially in the case of high density. The improvement in accuracy, in high density scenarios, is related to the number of received beacons during cell transit time T_s . Indeed, in high density scenarios, the number of exchanged beacons (during cell transit time T_s) during DC increases making polynomial modeling based estimation and Curve-fitting [45] in LSP more accurate. Whereas, in low-density scenarios, the number of beacons decreases considerably making polynomial modeling based estimation and Curve-fitting [45] in LSP less accurate. In average, the difference between the analytical and the simulation results is about 3%.

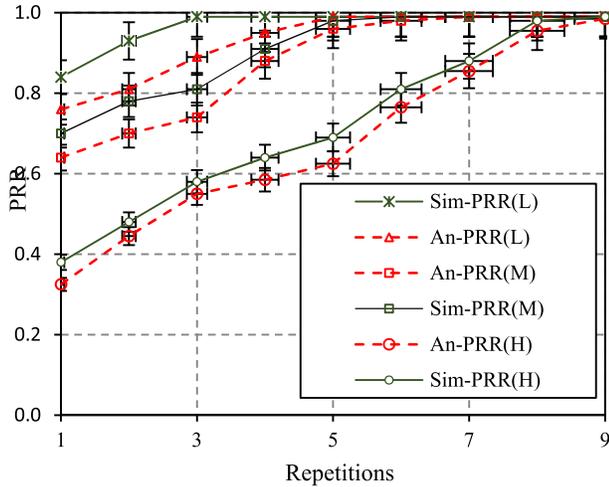


Fig. 6. PRR vs. Repetitions.

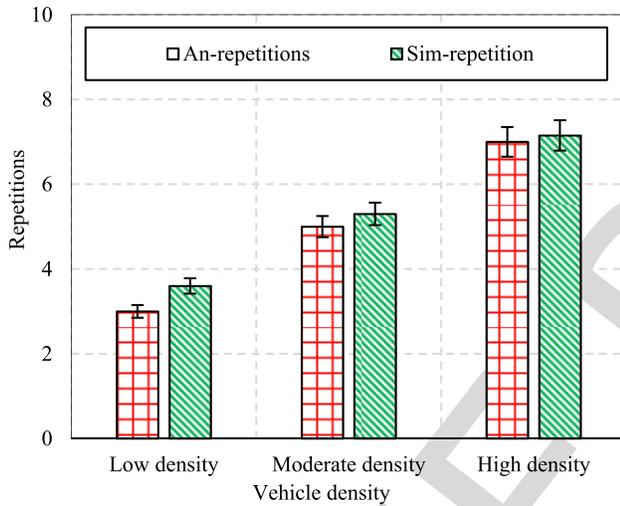
Fig. 7. Repetitions n_{opt} vs. density.

Fig. 6 shows PRR plotted against the number of repetitions n for three density levels. As expected, we observe that PRR increases with the number of repetitions. This observation validates the basic idea of broadcast repetitions. Again, the analytical results closely follow simulation results especially in moderate to high density scenarios. This behavior can be explained the same way the behavior, shown in Fig. 5, is explained (see previous paragraph). Fig. 6 shows that the average difference between the analytical results and simulation results is below 3%.

Fig. 7 shows repetitions n_{opt} plotted against density. We observe that the analytical model is very accurate: analytical results practically coincide with the simulation results, in both medium and high density cases. All simulation results in the plot are obtained with 94% confidence interval. Negligible differences, well below 5%, are noted only for low density scenarios.

C. Comparison

In this section, we evaluate the performance of REMD for city scenario in terms of PRR, average delay, and network

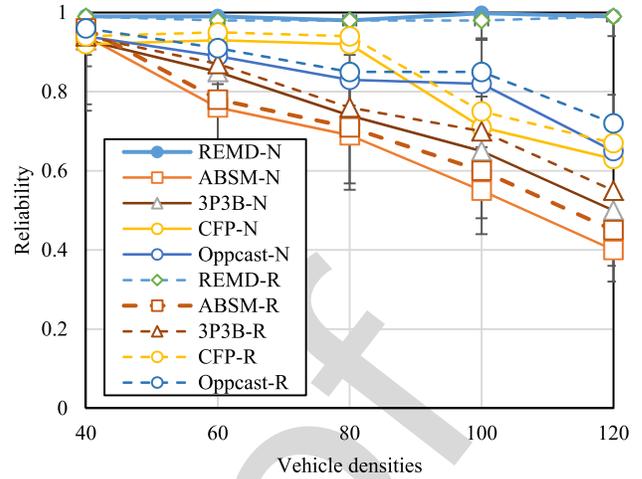


Fig. 8. PRR vs Vehicle density.

load. The performance results are shown in Figs. (8)–(10). Note that, in Figs. (8)–(10), we add a postfix “N” (respectively a postfix “R”) to the schemes names to indicate the performance results under Nakagami model (respectively under Rayleigh model).

Fig. 8 shows the variation of PRR for three density levels: high density (more than 80 vehicles/km), medium density (50–60 vehicles/km) and low vehicle density (Less than 40 vehicles/km). Initially, when the density is low, PRR varies between 95% and 99% for all schemes. Then, as the density increases, PRR gradually decreases to 66% for Oppcast-R, 57% for ABSM-R, 57% for 3P3B-R and 62% for CFP-R. More importantly, we observe that PRR degradation for all the schemes under Nakagami is worse than considering only Rayleigh. For example, ABSM-R records 47% while ABSM-N records 57%. The main reason for PRR degradation when considering Nakagami is that fading effects result in bad link reception quality. Hence, when vehicle density increases, channel conditions vary and in the presence of obstacles, signal strength gets low. In contrast, we observe that REMD-N and REMD-R has a constant PRR close to 99% for all densities. The main reason for PRR degradation when using the other schemes is that when vehicle density increases, channel conditions vary (as emulated by the Rayleigh model or the Nakagami model) resulting in bad link reception quality. In city environment, buildings and moving vehicles impact negatively the reception quality; when coupled with high vehicle density, the situation is much worse. When vehicle density increases, the number of vehicles in the interference range increases. This explains the poor performance of Oppcast since it does not implement a method to combat hidden terminal problem. In addition, Oppcast selects makeups (forwarders) based on their distance to the sender in order to improve packet reception for intermediate nodes. In high densities, makeups may have low reception quality resulting in packet loss. In ABSM, beacons include identifiers of the recently received broadcast messages, which serve as acknowledgement of successful message reception. Using this information, backbone nodes can check whether all their neighbors successfully received a message. If this is

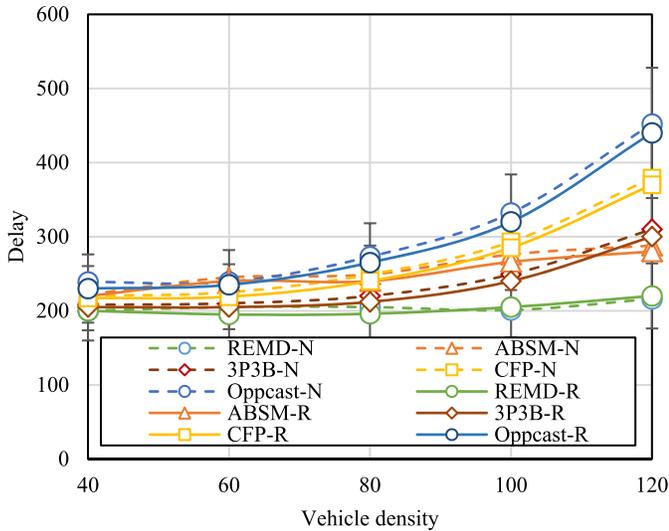


Fig. 9. Delay vs Vehicle density.

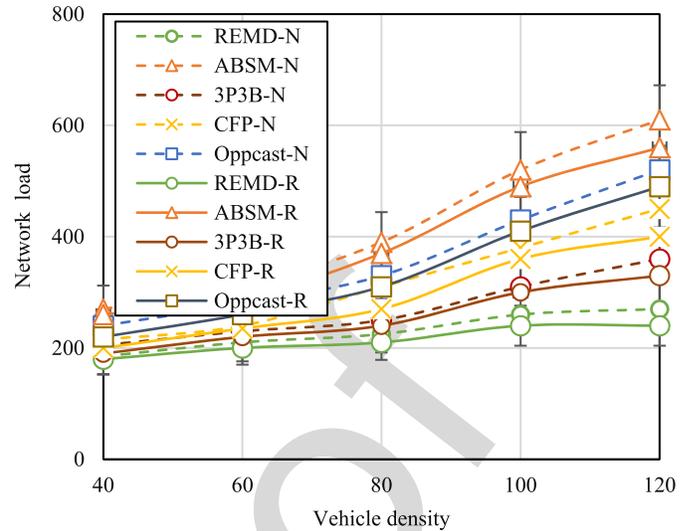


Fig. 10. Network Load vs Vehicle density.

not the case, a retransmission is scheduled upon the expiration of a timer. The higher the vehicle density, the higher the channel load and the higher the number of incurred collisions. In such a situation, a message may not be delivered to some passing vehicles which may be out of the sender range after the timer expires. In city settings, with high channel loss due to random interference, the resulting backbone links of ABSM are not reliable incurring high packet loss. PRR provided by 3P3B drops when vehicle density goes up. Link loss due to interference with beacons is a major problem. This situation becomes serious when vehicle density increases. Here, the key component (BTS/CTS handshake) in 3B3P is affected. Furthermore, 3P3B selects a remote neighboring node as next-hop forwarder which may move away or be out of range. The poor performance of CFP in city settings in terms of PRR is related to (a) the fixed number of repetitions. Indeed, channel loss increases with vehicle density; thus, few repetitions result in unreliability; and (b) the distributed code assignment method; indeed, messages exchanged between vehicles, for code availability information, are vulnerable to packet loss. In such a situation, several nodes may generate same repetition pattern resulting in unreliability. REMD, however, selects forwarders having good link reception quality. In high densities, collision rate and signal power attenuation rate drastically increase. In this case, REMD dynamically predicts/estimates (see DC and LSP for details) link reception quality in transmission range. Then, REMD carefully fixes the number of broadcast repetitions (in BR) in order to satisfy reliability requirement. Furthermore, REMD combats hidden terminal problem using UPOC.

Fig. 9 shows average delay plotted against vehicle density. We observe that REMD-N (respectively REMD-R) achieves a very close delay when compared to Oppcast-N and 3P3B-N (respectively Oppcast-R and 3P3B-R) for 40-60 vehicles/km. When vehicle density goes up, we observe that the gap between REMD-R and 3P3B-R (respectively REMD-N and 3P3B-N) becomes larger. A possible explanation is that, in dense urban scenarios, data packets may be highly vulnerable to packet loss (i.e., interference). This demonstrates

that packet loss due to background traffic (i.e., exchanged beacons) and hidden terminals critically impacts the delay performance of delay-based schemes (e.g., 3P3B). In such a situation, 3P3B performs more retransmissions in order to recover failed receptions. Indeed, exchanged messages are vulnerable to packet loss resulting in higher delay. For all vehicle densities, REMD keeps an average delay smaller than the recommended delay threshold [19]. This is due to the fact that (a) Forwarder selection (FS) phase considers distance to sender in addition to link reception quality; and (b) REMD employs fast repetitions. Even in the case of severe fading channel, REMD-N keeps an average delay smaller than the recommended delay threshold [14].

Fig. 10 shows that REMD generates lowest network load. More importantly, the total network load of REMD-N (or REMD-R) increases slowly with density. This is because the optimized broadcast repetitions mechanism in REMD avoids redundant rebroadcasting. The total network load generated by REMD-N is quite higher than REMD-R. This can be explained by the fact that in severe fading environment, more repetitions are required to ensure very high reliability. In opposition, Oppcast-R and 3P3B-R (respectively Oppcast-N and 3P3B-N) continue retransmitting in order to recover failed retransmissions. We conclude that REMD provides the best reliability compared to existing related schemes while, at the same time, provides the best delay which satisfies the requirements of safety applications.

VI. CONCLUSION

The proposed cell concept provides fine-grained information about wireless channel conditions. By employing curve fitting and polynomial modeling, we are able to predict/estimate an accurate link reception quality in cells. A Max-Min optimization problem is proposed to compute an optimal number of repetitions while ensuring predefined reliability requirements at each hop. A stochastic modeling approach is used to solve the Max-Min optimization problem. The number of successful receivers is computed from a Poisson Binomial

distribution (PBD). FFT enables an exact solution to PBD in $O(n \times \log(n))$. To combat hidden terminal problem, Uni-Polar orthogonal codes are applied to the city street network. This paper also proposes a solution for efficient next-hop forwarders selection. REMD selects multiple forwarders with good link reception quality together with their locations at each hop. The forwarders use cooperative transmissions with the objective to achieve high reliability in intermediate hops. Using simulations, we validated the analytical model of REMD. We evaluated, via simulations, the performance of REMD and did show its outperformance compared to existing related schemes. Future work will investigate the use of machine learning tools to improve the estimation accuracy of link qualities in different cells of a given zone.

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Wiem Benrhaïem received the M.Eng. degree and the M.Sc. degree in computer engineering from the National School of Engineers, Sfax, Tunisia, in 2010 and 2011, respectively, and the Ph.D. degree in computer science from the University of Montreal, Montreal, QC, Canada, in 2017. From 2009 to 2011, she was a Research Engineer with Telecom Sud-Paris, Evry, France. Her main research interests include machine learning, cloud computing, and connected vehicles.

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Abdelhakim Hafid was a Senior Research Scientist with Bell Communications Research (Bellcore), NJ, USA, where he spent several years focusing on the context of major research projects on the management of next generation networks. He was also an Assistant Professor with Western University (WU), Canada, the Research Director of the Advanced Communication Engineering Center (venture established by WU, Bell Canada, and Bay Networks), Canada, a Researcher with CRIM, Canada, a Visiting Scientist with GMD Fokus, Germany, and a Visiting Professor with the University of Evry, France. He is currently a Full Professor with the University of Montreal. He is also the Founding Director of the Network Research Laboratory and the Montreal Blockchain Laboratory. He is a Research Fellow of CIRRELT, Montreal, Canada. He has extensive academic and industrial research experience in the areas of management and design of next generation networks. He has published over 240 journal and conference papers. He holds three U.S. patents. His current research interests include IoT, fog/edge computing, blockchain, and intelligent transport systems.

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Pratap Kumar Sahu received the Ph.D. degree from National Central University, Zhongli District, Taiwan. Since 2015, he has been an Adjunct Professor with the Centurion University of Technology and Management, Bhubaneswar, India. He is currently a Post-Doctoral Researcher with the Network Research Laboratory, Department of Computer Science and Operation Research, University of Montreal, Montreal, QC, Canada. He has authored or co-authored many publications in journals, such as the *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS* and the *IEEE SENSORS*, and in conferences, such as the *IEEE Globecom*, the *IEEE ICC*, the *IEEE IWCMC*, and the *IEEE ICCCN*. His research interests include network coding, mobile clouds, vehicular ad hoc networks, and sensor networks. He served as a member of the Technical Program Committees of many conferences. He is also a Member of the *IEEE Communications Society*. He serves as an Associate Editor for the *Journal of Circuits, Systems, and Computers*. He served as a reviewer for many top journals and conferences.

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