NC–MAC: A Distributed MAC Protocol for Reliable Beacon Broadcasting in V2X

Hamed Mosavat-Jahromi, *Student Member, IEEE*, Yue Li, Lin Cai, *Fellow, IEEE*, and Lei Lu

***Abstract*—Beacon broadcasting is of great importance in improving road safety and avoiding dangerous situations in vehicular ad hoc networks (VANETs). In order to support emerging vehicular applications such as autonomous driving, the reliability of beacon broadcasting becomes an indispensable issue which is also difficult given the highly dynamic topology and vehicle density. For the territories which are not covered with communication infrastructure, controlling and scheduling in a centralized way may not be applicable. Therefore, vehicle-to-vehicle (V2V) ad hoc communication is promising to address the ubiquitousness coverage concern. In this paper, a distributed network coding-based medium access control protocol (NC–MAC) is proposed to support V2V beacon broadcasting. We combine the preamble-based feedback mechanism, retransmissions, and network coding together to enhance broadcasting reliability. Extensive simulations are given to show the performance gain of NC–MAC protocol compared to the existing 5 G cellular vehicle-to-everything (C–V2X) MAC protocol in a wide range of scenarios including highway and urban vehicle traces generated by simulation of urban mobility (SUMO). The results show that the proposed protocol can improve the communication reliability as well as scalability.**

***Index Terms*—Vehicular ad hoc network (VANET), vehicle-to-everything (V2X), distributed MAC, reliability, wireless communication.**

I. Introduction

The key component of intelligent transportation systems (ITS) evolution as well as automotive revolution is connected vehicles. With the information exchange among vehicles, roadside infrastructures, pedestrians, and clouds, connected vehicles can sense more precisely and make imperative decisions comparable to human drivers, leading to a higher efficiency transportation and energy, higher level of safety, lower amount of CO_2, and in-car entertainments [2]–[4].

Vehicle-to-everything (V2X) is a general term covering vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), etc. [5]. Beacon message broadcasting is the pillar of the V2X systems. Generally, beacon messages may include locally sensed data, vehicles' status information, and safety-related messages. Beacon broadcasting can play an important role in enhancing road safety. When a road is covered by communication infrastructure, e.g., base stations or road side units, transmissions are controlled and scheduled in a centralized way. However, there are still territories which have not been covered by cellular systems. Therefore, V2V communication is a potential way for the vehicles to broadcast and collect beacon messages. Furthermore, due to uneven traffic in time and space, communication channels may be overloaded, specially in high density scenarios, causing beacon collisions or losses. Indisputably, reliable beacon broadcasting is of great importance for safety-related applications.

In order to support high performance and ubiquitous communications, different V2X technologies have been proposed. Dedicated short-range communications (DSRC) and cellular V2X (C–V2X) are two major V2X technologies [6].

- *DSRC:* DSRC's physical and medium access control (MAC) layers are specified in the IEEE 802.11p standard. Although the MAC protocol in the DSRC is distributed and simple, it suffers from poor scalability and low performance in high-mobility scenarios [7]. It does not have any acknowledgement (ACK) mechanism for broadcasting.
- *C–V2X:* The 3rd Generation Partnership Project (3GPP) has developed C–V2X which is a Long Term Evolution (LTE)-based radio access technology. It enables vehicles to communicate distributedly over a sufficiently large communication range. It has also been designed to keep the network operating both in and out of network coverage scenarios [7]–[9].

The reliability of beacon transmission is a key issue in V2X. Reception of unreliable safety-related messages would defeat the purpose of beaconing leading to public safety concerns. In this paper, we consider C–V2X and the scenarios without a centralized controller from infrastructures, where transmission collision, limited communication range, and unreliable transmissions are the main challenges for reliable beacon broadcasting.

Compared to the LTE sidelink mechanism, a more compact resource allocation scheme has been introduced for the physical sidelink control and shared channels in 5G C–V2X [10]. According to the new scheme, the latency and collisions can be reduced by deployment of the semi-persistent scheduling and sensing-oriented access scheme [11], [12]. In Release–15, the resource sharing method between mode–3 and mode–4 users

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has been investigated. However, an additional control overhead is introduced to avoid any collisions, and the collisions problem remains unsolved when users are out of coverage of cellular network.

Although a larger broadcasting range and higher transmission power may help vehicles to collect more beacons and ensure a higher signal-to-noise-ratio (SNR), respectively, they naturally intensifies the collisions on the air-interface. In the current C–V2X system, not only are collisions inevitable, but also there is no hybrid automatic repeat request (HARQ) feedback for broadcasting [11]. Without the HARQ feedback, collisions are undetectable and cannot be stopped timely. Therefore, the reliability of beaconing cannot be guaranteed. Blind HARQ retransmissions have been proposed to improve the reliability the V2X systems, which, however, are not efficient from the resource usage point of view. This paper is to fill the gap to support reliable and scalable beacon broadcasting. The main contributions of this paper are three-fold. First, we propose a novel network coding-based distributed MAC protocol (NC–MAC) which can substantially increase the reliability of the beacon transmission. The fully distributed solution can foster the roll-out of V2X technologies. We employ a preamble mechanism in the frame structure to report a negative ACK (NACK) and request a retransmission. We apply the NC mechanism to generate independent linear combinations of messages. Therefore, more neighbors in a larger broadcasting range can receive beacons. Moreover, it can help to recover missed beacons. By combining the HARQ and NC schemes together, we substantially reduce the loss probability. Second, we develop an analytical framework to quantify the performance of the proposed MAC which can be used to guide the system parameter settings. Third, we use the simulation of urban mobility (SUMO) [13] to generate two typical traffic scenarios, highway and urban, using different vehicles with different attributes. Simulation results corresponding to different mobility scenarios have validated the design and demonstrated the performance gain of the proposed solution.

The rest of the paper is organized as follows. In Section II, related work on the existing MAC protocols and NC technique are described. Section III presents the protocol design. Corresponding simulation results are given in Section V, followed by the conclusions in Section VI.

II. Related Work

A. Distributed MAC

The IEEE 802.11p standard has been proposed for wireless access in vehicular communication networks. This standard utilizes the carrier sense multiple access/collision avoidance (CSMA/CA) protocol. However, its performance deteriorates dramatically in high density scenarios.

For broadcasting, the ACK mechanism is removed due to ACK flooding and collisions. Therefore, reliability cannot be guaranteed. Consequently, undetectable collisions and hidden terminal problem remain unsolved, where two users compete for the same resource for transmissions [14], [15]. The European Telecommunications Standards Institute (ETSI) has adopted an asynchronous decentralized congestion control (DCC) protocol [16]. In this protocol, different transmission power levels, beaconing frequencies, and data rate are determined according to the channel busy ratio. The proposed protocol is not efficient in periodic safety message distributions [17].

The proposed MAC protocol in [18], CTMAC, combines the CSMA and time division multiple access (TDMA) strategies. The strategy is chosen corresponding to the instantaneous vehicle density. It reduces the number of collisions along with the access delay compared to the earlier protocols. Basically, due to the dynamic of V2X, it is difficult if not impossible to ensure high resource utilization, high reliability, and low collision probability communication with CSMA-based approaches. TDMA-based MAC protocols were proposed to address these problems.

Although TDMA needs time synchronization to access different time slots, it is still one of the main choices in collision-free MAC protocols. Reference [19] has developed a multichannel TDMA protocol. It provides a single- or multi-hop broadcasting by assigning disjoint sets of time slots to roadside units and vehicles moving in the opposite directions. The hidden terminal problem has been alleviated in this protocol, while the overhead may affect network throughput.

MoMAC, a TDMA-based approach, is introduced in [20]. In this protocol, each frame is divided into different sections corresponding to different lanes, directions, and intersections. The information related to one-hop nodes is stored in the header of each packet which may increase the signaling overhead. Moreover, the protocol may face resource underutilization when the densities of traffic in two directions are highly different.

Reference [21] has introduced SCMAC which focuses on cooperative medium access control. It exploits the TDMA access method, and the future state of the channel is broadcast through the cooperative beaconing process. The beaconing period is adaptive and determined according to the instantaneous vehicle density. The hidden terminal has not been fully considered in this work, which may cause unexpected packet losses and degrade communication reliability. How to design a scalable and reliable distributed MAC for V2X remains an open issue.

The time slot-sharing MAC (SS-MAC) approach proposed in [22] for distributed periodical message broadcasting. It supports different beaconing rates. In this work, after collecting occupancy states, time slots are shared among different users. Two algorithms were proposed for slot sharing and vehicle-slot sharing in this work. Broadcasting frame information from neighbor nodes to select time slot plays an important role in SS-MAC in order to detect collisions. In dense networks, multiple new users within each other's broadcasting range may access the channel simultaneously, which results in an unreliable communication. How to avoid and detect collisions remain an open issue in dense scenarios.

B. Network Coding

NC has been extensively studied in recent years [23]–[25]. A sender combines successfully received original packets and generate new a packet using their linear combination. The coefficients and operations are done in a Galois field [26]. When the received linear combinations construct a full-rank matrix, the receiver can recover the original packets included in the linear combination by solving a system of linear equations. NC has been proposed for local data exchange and cellular communications [27], for enhancing transmission efficiency and reliability.

Random linear network coding (RLNC) has been applied to the cellular multicast channels in [28], [29]. Comprehensive performance analysis of using NC and device-to-device communication in the cellular systems are shown in [26] and [30], for downlink and uplink scenarios, respectively.

Considering NC's advantages in packet exchange and broadcast/multicast scenarios, it is applicable to the vehicular ad hoc networks (VANETs). Reference [31] exploited NC for data exchange between vehicles and roadside base stations. A random coefficient generation method was proposed in [32] for the linear combinations to enhance both security and reliability. NC was applied in a multi-hop broadcasting protocol in [33]. It reduces the total number of transmissions and improves the packet dissemination ratio. Although it has been assumed that the vehicles in a network are aware of the global information, the detailed signaling design and corresponding control overhead as well as resource allocation and collision avoidance were not addressed yet.

Though the existing works applying NC to the vehicular network demonstrate a promising direction, the protocol design issues including collision, reliability, and communication range remains open. A practical protocol needs to be designed in detail to support the required functions and performance. The main challenge is how to ensure reliability of beacon broadcasting in a mobile ad hoc network with time-varying, error-prone wireless channels, and hidden terminals. In order to increase the reliability in V2V communications, we deploy NACK and retransmission mechanisms as well as the network coding scheme which increase the chance of recovering a missed beacon. Moreover, by deployment of different preambles, the hidden terminal problem may be detected and resolved timely, which results in less access collision and higher performance compared to the contention-based protocols. In the aforementioned state-of-the-art protocols, neither have these aspects been considered, nor network coding scheme has been deployed.

In the next section, we introduce the design of NC–MAC, which uses network coding-based diversity transmissions, NACK, and orthogonal preamble design to address the above mentioned challenge.

III. NC–MAC Design

A. Protocol in a Nut-Shell

In the NC–MAC, similar to 5G C–V2X [7], time in a period is divided into time slots, and the available bandwidth is divided into several sub-channels. The medium access protocol is a TDMA-based one. Time synchronization is achieved assuming that each vehicle (VE) can use the global positioning system (GPS). However, if the GPS signal is lost, it is assumed that the GPS local oscillator is stable enough to keep the users synchronized. Each VE in the V2X system can acquire an

Fig. 1. The structure of a resource block in NC–MAC protocol.

available resource block successfully through a resource request and allocation process [34]. Therefore, VEs always broadcast beacon messages to their neighbors on their dedicated resource blocks. The basic principles of transmissions in an allocated resource block are summarized as follows:

1) Each resource block consists of three parts, including a preamble part and two data transmission opportunities. The structure of a resource block is depicted in Fig. 1.
2) Preambles are orthogonal sequences responsible for resolution of collisions and assisting NACKs during the accessing and beaconing processes, respectively. Different types of preambles use orthogonal codes. Therefore, they are detectable even when collisions happen. The preambles which are used in accessing and beaconing processes have been explained in detail in [34].
3) In the two transmission opportunities, each VE sends its own original message and an independent linear combination of its own original beacon message and the previously received beacons from others that need to be retransmitted on the first and the second transmission opportunities, respectively. If there is no other beacon to send, its own original beacon message will be transmitted twice using the two transmission opportunities.
4) When a vehicle fails to receive an original message, a *preambleN* is sent on the preamble part.

A beacon message may be sent directly or included in a linear combination according to the NC principles. If a user fails to receive an original message due to poor channel condition or failure in the recovering process, a NACK is reported on a common feedback channel which is monitored by all of the VEs in the system. According to the above feedback mechanism, transmission failures are detectable and the NACKs coming from multiple users can be considered as diversity reception. By reception of a NACK, it implies that at least a user has failed to receive the corresponding message within a certain beacon range.

B. Diversity Transmissions With Linear Combinations

A user may broadcast linear combinations of the previously received messages based on the received NACKs. These linear combinations can be used to recover transmission failures and/or multi-hop forwarding. The full set of coefficient vectors are known by all devices, and they can use the index to refer to different coefficient vector. The header of the protocol data unit (PDU) contains this information. Fig. 2 shows how NC–MAC works in an example.

At the beginning of the beaconing process, *VE1* sends its original message, *Message1*. It is successfully received by *VE3–5*, while *VE2* fails to receive it. It sends a *preambleN* on the common

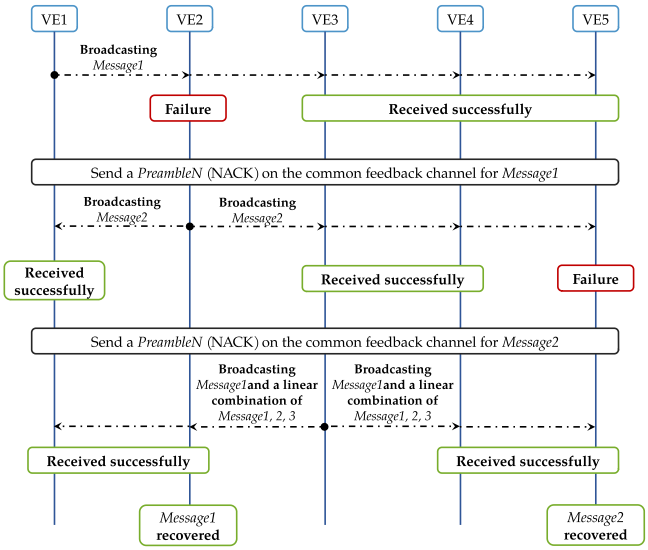


Fig. 2. An example of NC–MAC protocol.

feedback channel to notify the failure. *VE2* starts sending *Message2* in the next time slot which is successfully received by other VEs except by *VE5*. *VE3* broadcasts a *preambleN* to notify the failed reception. After reception of the NACKs corresponding to *Message1* and *Message2*, *VE3* is notified that the messages have not been successfully received by some users. Thus, it sends its own beacon on the first transmission opportunity, and generates and sends a linear combination using the successfully received messages and its own beacon in the second transmission opportunity as follows,

$$C_1 = \alpha_{13} m_3,$$
$$C_2 = \alpha_{21} m_1 + \alpha_{22} m_2 + \alpha_{23} m_3, \tag{1}$$

where C_1, C_2 are the two linear combinations, and m_1, m_2, m_3 are the original beacon messages sent by *VE1*, *VE2*, and *VE3*, respectively. Each linear combination consists of a coefficient vector and three original packets, $\alpha_{ij} \in GF(2^k); i = 1, 2, j = 1, 2, 3$. Note that each *VE* also includes its own original message in the linear combination. It this case, *VE3* needs to decode m_1 and m_2 first. After decoding m_1 and m_2, *VE3* can generate the above linear combinations to send. Since *VE2* has its own message, m_2, if it successfully receives C_1, C_2, it can build a coefficient matrix A as follows,

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \end{bmatrix}. \tag{2}$$

If A is a full-rank matrix, *VE2* can recover m_1 by solving the system of equations. The independent coefficients of the linear combination can be achieved from the well-known Vandermonde matrix which is a full-rank matrix if its entries are distinct.

$$\begin{bmatrix} m_1 \\ m_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \alpha_{21} & \alpha_{23} \end{bmatrix}^{-1} \begin{bmatrix} C_1 \\ C_2 - \alpha_{22} m_2 \end{bmatrix}. \tag{3}$$

The same procedure may be carried out by *VE5* in order to recover the missed *Message2*.

C. Forwarding Principles

Each VE maintains a neighbor list as well as two independent queues. The neighbor list is kept updated by the received signal-to-interference-plus-noise ratio (SINR) and the VEs in this list are supposed to receive the transmitted beacon. The original queue stores the VE's own beacon messages and the forwarding queue stores other VEs' messages that need to be forwarded. If a VE successfully receives an original message and at the same time, it detects a NACK in the feedback channel from a VE in the neighbor list, the received message is considered as a forwarding message and added to a forwarding queue.

If the forwarding queue is not empty at the time of transmission, a linear combination is generated using the VE's own message and the K oldest forwarding messages in the forwarding queue. $K = \min[F_s, F_l]$, where F_s and F_l are the size of the forwarding queue according to the protocol's setting and the length of the queue, i.e., number of the existing forwarding messages in the forwarding queue, respectively.

Once the beacons in the forwarding queue are sent in a linear combination, they are removed from the queue. In other words, each message can be forwarded once per VE. We assume that the beacon messages have a limited lifetime and they expire after a period since a new beacon will be generated periodically and make the old one useless.

D. Feedback

In order to reflect the transmission needs, the forwarding/retransmission procedure should be well-designed. The NACK mechanism plays a pivotal role in this regard. To have an active NACK mechanism, a VE should report a NACK on the pre-configured feedback channel if

- a message is expected to be received on a certain resource block, but the receiver fails to decode or detect the signal; or
- a linear combination is successfully received, but the receiver fails to recover the sender's own message from it.

In Fig. 2, for example, if *VE1* transmits *Message1* twice and *VE2* receives none of them, *VE2* broadcasts a NACK. Also, if *VE2* receives one linear combination but cannot recover the sender's message, *Message1*, it broadcasts a NACK.

Whether a user should expect beacon messages on a specific resource block depends on the user's neighbor list. Each user maintains and updates its neighbor list according to the SINR of the received messages on all of the resource blocks. The updating procedure is based on the long-term averaged results to avoid any ping-pong effects. Temporary poor channels will be compensated by NACK reporting and other's forwarding as proposed in NC–MAC.

Reception of a NACK is also dependent on the averaged SINR threshold. A VE can forward a missing beacon only if it receives the corresponding NACK. Evidently, the received power of the NACK should be above a certain threshold. By adjusting this threshold, the forwarding scale can be controlled. A lower threshold results in more VEs to forward the beacon.

The computation complexity of generating linear combinations and recovering missed beacons from the linear combinations are $\mathcal{O}(N^2 L)$ and $\mathcal{O}(M^3 + M^2 L)$, respectively, where N, M, and L are the number of beacons in the forwarding queue, number of linear combinations, and length of a transmission opportunity in a beacon [26]. The N^3 comes from the computational complexity of Gauss-Jordan elimination. The size of a transmission opportunity is regularly as small as hundred bytes. However, the number of beacons which should be included in the linear combination, N, can be adjusted by the forwarding queue's size. Also, the number of received linear combinations, M (i.e. F_s), is dependent on the vehicles density, the total number of vehicles in the receiving range of a vehicle, and beacon reception error. Therefore, the complexity of these operations is adjustable depending on the memory and computational strength of vehicles.

IV. Theoretical Analysis

In order to evaluate the performance of NC–MAC in terms of delay and reliability, the very first step is to find the probability mass function (PMF) of the needed number of transmissions to enable a receiver to recover a certain beacon message. Either a beacon message is sent originally or forwarded by a user's linear combination, it is considered as one transmission.

A. PMF of the Number of Transmissions

In order to find the PMF of the number of transmissions, we assume that by each resource block, an original beacon and an independent linear combination of the original beacon and previous successfully received beacons are transmitted, which help a receiver to recover the missing beacons. Here, we introduce a variable named level of deficiency (LoD) which is equal to or less than zero and indicates how many more linear combinations a user needs to have a full-rank coefficient matrix and be able to recover the missing beacons. Upon reception of a linear combination, the receiver expects a new beacon associated with the transmitter. We need to consider three cases. First, if the receiver receives both the original message and the linear combination successfully, the LoD is increased by one since the linear combination may be used in the recovery of the missing beacons. Second, either the original message or the linear combination is missed, the LoD will not change, due to the fact that the received packet may not change the rank of matrix A in (2). In other words, by considering the coefficient matrix A, there is a new variable and a new equation corresponding to the received packet on the transmission opportunity. In the last case, if no packet is received, the LoD will decrease by one. Here, the aim is to find the probability that the LoD of a user which is zero initially, reaches zero after n transmissions.

We model the transmissions as a sequence, i.e., $\mathbb{X}_n^r = \{X_1, \ldots, X_n\}$ where $X_i \in \{-1, 0, +1\}$, n is the number of transmissions, and r stands for the initial state of LoD. $X_i = 0, +1$ represent successful reception of one and two linear combinations, respectively. Failure reception of both linear combinations corresponds to $X_i = -1$. The probabilities of different possibilities of X_i are given by

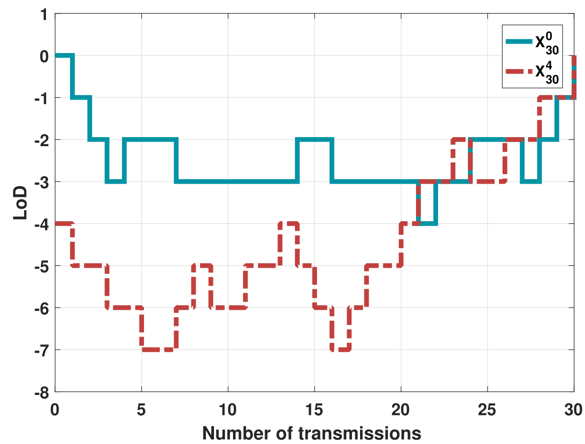


Fig. 3. Examples of possible sequences for $\mathbb{X}_{30}^0$ and $\mathbb{X}_{30}^4$.

$$\Pr(X_i) = \begin{cases} p_1, & X_i = 1, \\ p_0, & X_i = 0, \\ p_{-1}, & X_i = -1, \end{cases}$$

which are dependent on channel fluctuations and redundancy of the received linear combinations.

1) Zero-Initial LoD: The initial state of the LoD is zero in this case, i.e., $r = 0$, meaning that the receiver has all of the previously transmitted beacons in a period. Fig. 3 shows an example of this sequence. $\mathbb{X}_n^0$ is considered as a possible sequence that right after n steps, LoD returns zero. The $\mathbb{X}_n^0$ should satisfy the following constraints:

$$\begin{aligned} &X_1 = -1, \\ &X_1 + X_2 < 0, \\ &X_1 + X_2 + X_3 < 0, \\ &X_1 + X_2 + X_3 + X_4 < 0, \\ &\qquad\vdots \\ &X_1 + X_2 + X_3 + \cdots + X_{n-1} < 0, \\ &X_1 + X_2 + \cdots + X_n = 0,\ X_n = +1, \end{aligned} \tag{4}$$

and its matrix form is

$$\begin{bmatrix} 1 & 0 & 0 & 0 & \ldots & 0 \\ 1 & 1 & 0 & 0 & \ldots & 0 \\ 1 & 1 & 1 & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & 1 & \ldots & 1 \end{bmatrix} \begin{bmatrix} X_2 \\ X_3 \\ X_4 \\ \vdots \\ X_{n-1} \end{bmatrix} < \begin{bmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} \tag{5}$$

Therefore, the PMF of the needed number of transmissions is defined as

$$P_N^0(n) = \Pr\left[\sum_{i=1}^{n} X_i = 0,\ X_1 = -1,\ X_n = 1,\ (5)\right]. \tag{6}$$

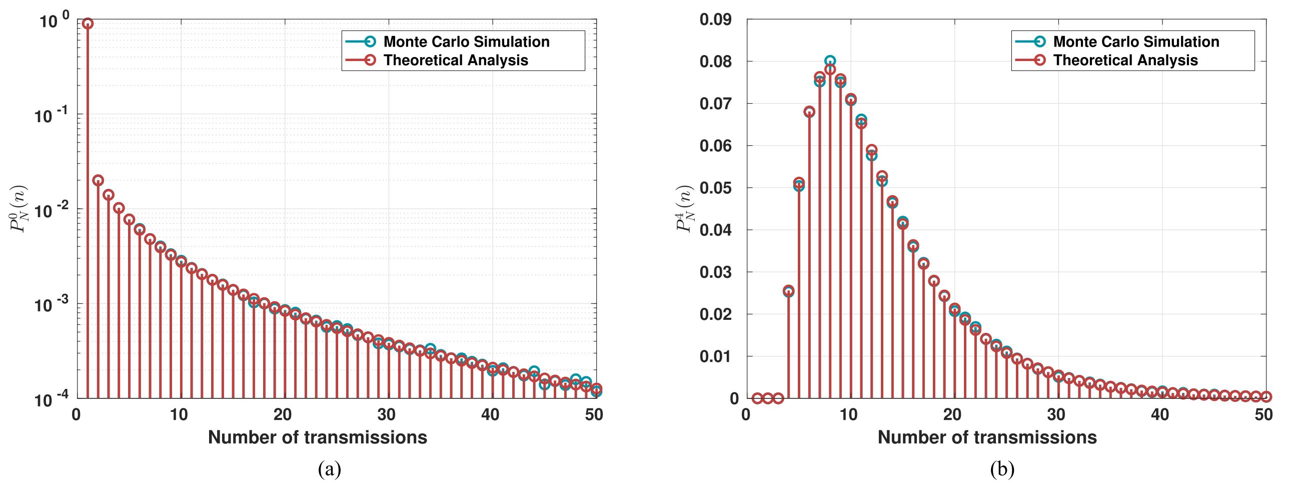


Fig. 4. Monte Carlo validation of $P_N^0(n)$ and $P_N^4(n)$. (a) $P_N^0(n)$ with $p_1 = 0.2, p_0 = 0.7, p_{-1} = 0.1$. (b) $P_N^4(n)$ with $p_1 = 0.4, p_0 = 0.5, p_{-1} = 0.1, r = 4$.

Since the zeros do not change any of the constraints in (4), we first focus on finding the total number of ways to distribute Q number of $+1$ and Q number of -1 within $\mathbb{X}_n^0$ such that it satisfies the constraints in (4). Afterwards, $n - 2Q$ zeros can be distributed among the already distributed $+1$s and -1s. For example, the possible $\mathbb{X}_{30}^0$ in Fig. 3 consists of the following sequence of $+1$ and -1 which have $\mathbb{Z}_t$, $t = 1, \dots, 2Q - 1$, all-zero sequences in between.

$$\mathbb{X}_{30}^0 = \Big\{ -1, \mathbb{Z}_1, -1, \mathbb{Z}_2, -1, \mathbb{Z}_3, \dots, +1, \mathbb{Z}_{2Q-1}, +1 \Big\}, \quad (7)$$

The problem of finding the total number of non-zero sequences satisfying the constraints in (4) has been studied in [35] as a random walk problem which starts from and returns to the origin after $2Q$ steps. The total number of possible non-zero sequences is [35]

$$\frac{1}{2\,(2Q-1)}\binom{2Q}{Q}. \quad (8)$$

Now, we can find the total number of ways which zeros can be distributed in different $\mathbb{Z}_t$, $t = 1, 2, \dots, 2Q - 1$ in (7). The total number of possible all-zero sequences which overall have $n - 2Q$ zeros can be found by enumerating possible choices, and it is obtained by solving the following equation

$$|\mathbb{Z}_1| + |\mathbb{Z}_2| + |\mathbb{Z}_3| + \cdots + |\mathbb{Z}_{2Q-1}| = n - 2Q, \quad |\mathbb{Z}_t| \geq 0. \quad (9)$$

where $|\,.\,|$ represents cardinality of Z_t. The equation in (9) has $\binom{n-2}{2Q-2}$ solutions. Since $\mathbb{X}_n^0$ may have at most $\lfloor \frac{n}{2} \rfloor$ number of $+1$ and -1, the total number of $\mathbb{X}_n^0$ satisfying the constraints in (5) is

$$|\mathbb{X}_n^0| = \sum_{Q=1}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{2\,(2Q-1)}\binom{n-2}{2Q-2}\binom{2Q}{Q}. \quad (10)$$

Now, finding the probability of occurrence of $\mathbb{X}_n^0$ according to the constraints in (4) is straightforward based on this analysis. This PMF is as follows

$$P_N^0(n) = \begin{cases} 1 - p_{-1}, & n = 1, \\ P_n^0, & n \geq 2, \end{cases}$$

where P_n^0 is

$$P_n^0 = \sum_{Q=1}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{2\,(2Q-1)}\binom{n-2}{2Q-2}\binom{2Q}{Q}(p_1\, p_{-1})^Q\, p_0^{n-2Q}. \quad (11)$$

The results from the theoretical analysis and Monte Carlo simulation match well, as shown in Fig. 4 (a) for $p_1 = 0.2$, $p_0 = 0.7$, and $p_{-1} = 0.1$.

2) Non-Zero-Initial LoD: Next, we can extend what was achieved in (11) to a general case, i.e., $P_N^r(n)$ given the initial LoD of r, $r = 1, 2, 3, \dots$. For the $\mathbb{X}_n^r$ whose starting point is r and ends at zero, obviously $n \geq r$ and the set of inequality constraints presented in (5) are modified as

$$\begin{bmatrix} 1 & 0 & 0 & 0 & \dots & 0 \\ 1 & 1 & 0 & 0 & \dots & 0 \\ 1 & 1 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & 1 & \dots & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_{n-1} \end{bmatrix} < \begin{bmatrix} r \\ r \\ r \\ \vdots \\ r \end{bmatrix} \quad (12)$$

The same as the previous proof, Q, S, and Z represent the total number of $+1$, -1, and 0 in $\mathbb{X}_n^r$, respectively. A set of equations can be written on Q, S, and Z as

$$\begin{aligned} Q - S &= r, & \Longrightarrow \quad Q &= \frac{n - Z + r}{2}, \\ Q + S &= n - Z, & \Longrightarrow \quad S &= \frac{n - Z - r}{2}. \end{aligned} \quad (13)$$

According to the famous ballot theorem in [35], the total number of possible $\mathbb{X}_n^r$ which only consists of $+1$ and -1 is

$$\frac{r}{Q+S}\binom{Q+S}{\frac{Q+S+r}{2}}. \quad (14)$$

The next step is to distribute Z number of zeros by inserting sets of zeros, $\mathbb{Z}_t$, $t = 1, 2, \ldots, Q + S$ among $+1$ and -1 of the $\mathbb{X}_r^n$. With the same argument in (7), there are totally $Q + S$ spots to distribute zeros. Therefore, the total number of ways to distribute Z zeros among these $Q + S$ spots can be enumerated by solving the following equation.

$$|\mathbb{Z}_1| + |\mathbb{Z}_2| + |\mathbb{Z}_3| + \cdots + |\mathbb{Z}_{Q+S}| = Z, \quad |\mathbb{Z}_t| \geq 0, \tag{15}$$

where $|.|$ represents cardinality of $\mathbb{Z}_t$. This equation has $\binom{Z+Q+S-1}{Q+S-1} = \binom{n-1}{n-Z-1}$ number of solutions. By multiplying the results in (15) and $\frac{r}{Q+S}\binom{Q+S}{\frac{Q+S+r}{2}}$, and summing over Z, the total number of $\mathbb{X}_n^r$ is

$$|\mathbb{X}_n^r| = \sum_{Z=0}^{n-r} \frac{r}{n-Z}\binom{n-Z}{\frac{n-Z+r}{2}}\binom{n-1}{n-Z-1}\mathcal{I}(Z), \tag{16}$$

where $\mathcal{I}(Z)$ is defined as

$$\mathcal{I}(Z) = \begin{cases} \frac{1+(-1)^Z}{2}, & \mathrm{mod}(n-r, 2) = 0, \\ \frac{1-(-1)^Z}{2}, & \mathrm{mod}(n-r, 2) = 1. \end{cases} \tag{17}$$

According to the total number of sequences starting form LoD of r and ending at zero in (16), the corresponding PMF is

$$P_N^r(n) = \sum_{Z=0}^{n-r} \frac{r}{n-Z}\binom{n-Z}{\frac{n-Z+r}{2}}\binom{n-1}{n-Z-1}\mathcal{I}(Z)p_{-1}^S p_0^Z p_1^Q, \quad n \geq r, \tag{18}$$

where Q and S are found as functions of n, r, and Z from (13). The results from the theoretical analysis and Monte Carlo simulation are shown in Fig. 4 (b) for $p_1 = 0.4$, $p_0 = 0.5$, and $p_{-1} = 0.1$.

B. Modeling p_{-1}, p_0, and p_1

Assuming that the neighbor list and the NACK receiving range are based on the averaged SINR, and applying the same large-scale fading channel model to every VE, the neighbor list and the NACK receiving range can be approximately modeled by the distance between the transmitter and the receiver. The variables $D^{(rx)}$ and $D^{(nack)}$ are defined as the receiving range and feedback range, respectively. The receiving range is assumed to be smaller than the communication range to limit the number of target vehicles. Any two VEs with a distance less than $D^{(rx)}$ are considered as each other's neighbors, and VEs within the distance of $D^{(nack)}$, can successfully receive the transmitted NACKs. Since reporting a NACK to a VE farther than $D^{(rx)}$ is not necessary, $D^{(nack)}$ is assumed to be less than $D^{(rx)}$ to avoid any possible waste of resources. The probabilities of p_{-1}, p_0, and p_1 are all dependent of the previous received or non-received beacons. In the following, we use some approximations to simplify the analysis.

1) p_{-1}: It is defined as the probability that a receiver receives neither the original beacon on the first transmission opportunity nor the linear combination on the second one corresponding to a neighboring VE. This probability is modeled as

$$p_{-1} = \Pr[A_1, F_1, F_2] + \Pr[A_1, F_1, \overline{F_2}, U], \tag{19}$$

where A_1 is the event that the transmitter is in the receiver's neighbor list, i.e., $d \leq D^{(rx)}$, F_1 and F_2 denote the events that the receiver fails to receive the first and the second transmission opportunities, respectively. Evidently, their complementary sets represent successful receiving. Moreover, U denotes the event where the received linear combination includes unwanted beacon messages, i.e., the messages which originally sent by the VEs who are not in the neighbor list. Receiving a linear combination containing a message from a non-neighbor VE makes the whole linear combination useless due to recovery impossibility. The probability given in (19) includes two cases which may result in a decrease in the LoD. Failure in reception of the transmission opportunities and reception of a linear combination which contains an unwanted message, both cause a decrease in the LoD.

The probability of the above event is approximated as follows.

$$\begin{aligned} \Pr[A_1] &= \int_0^{+\infty} \Pr[A_1 | D_s = x] f_{D_s}(x)\mathrm{d}x \\ &= \int_0^{+\infty} \min\left[\frac{2D^{(rx)}}{x}, 1\right] f_{D_s}(x)\mathrm{d}x \\ &\approx \min\left[\frac{2D^{(rx)}}{\mathbb{E}[D_s]}, 1\right], \end{aligned} \tag{20}$$

where D_s is the reuse distance, i.e., the distance between two VEs using the same resource, and $f_{D_s}(x)$ is the corresponding probability distribution function (PDF). The PDF of D_s depends on sensing sensitivity in the accessing procedure. The reuse distance is a function of the vehicle density and number of available resources. In order to approximate $\Pr[A_1]$, the expectation of D_s, $\mathbb{E}[D_s]$ was used in (20) according to the Taylor expansion for the first moment of function of a random variable [36]. In the theoretical analysis and evaluation, we assume that the reuse distance equals the length of the road.

We assume that two transmission opportunities experiencing the same error distribution on the channel, and $F_1|A_1$ and $F_2|A_1$ are two correlated Bernoulli events where $\Pr[F_1|A_1] = \Pr[F_2|A_1] = p_e$ and p_e denotes block/packet error rate (BLER). Covariance of these two events which represents temporal correlation of the communication channel over two successive transmission opportunities in the same resource unit is $Cov[F_1, F_2|A_1] = \mathbb{E}[F_1, F_2|A_1] - \mathbb{E}[F_1|A_1]\mathbb{E}[F_2|A_1]$, and also, $\Pr[F_1, F_2|A_1] = \mathbb{E}[F_1, F_2|A_1]$. The Pearson correlation coefficient, ρ, in terms of $Cov[F_1, F_2|A_1]$ and p_e is

$$\rho = \frac{Cov[F_1, F_2|A_1]}{\sigma_{F_1|A_1}\sigma_{F_2|A_1}} = \frac{\mathbb{E}[F_1, F_2|A_1] - \mathbb{E}[F_1|A_1]\mathbb{E}[F_2|A_1]}{p_e(1-p_e)}. \tag{21}$$

Therefore, the first term in (19) is modeled as

$$\begin{aligned} \Pr[A_1, F_1, F_2] &= \Pr[A_1]\Pr[F_1, F_2|A_1] = \Pr[A_1]\mathbb{E}[F_1, F_2|A_1] \\ &= \Pr[A_1]\left(\mathbb{E}[F_1|A_1]\mathbb{E}[F_2|A_1] + Cov[\epsilon_1, \epsilon_2]\right) \end{aligned}$$

$$\approx \min\left[\frac{2D^{(rx)}}{\mathbb{E}[D_s]}, 1\right]\left(p_e^2 + \rho p_e(1-p_e)\right). \tag{22}$$

It is assumed that each VE's channel is a stationary random process and the PDF of the received signal-to-noise ratio (SNR) given the transmission distance, d, is denoted by $f_{\mathrm{SNR}|d}(x)$. In order to decode the received message successfully, the SNR needs to be above a certain threshold, SNR_T. Considering the received SNR and distance probability distributions, the BLER is obtained as follows

$$p_e = \int_0^{D^{(rx)}}\int_0^{\mathrm{SNR}_T} f_{\mathrm{SNR}|d}(x) f_d(y)\mathrm{d}x\mathrm{d}y. \tag{23}$$

By considering a Rayleigh fading channel and a device-to-device communication path loss model, p_e is achieved as

$$\begin{aligned} p_e &= \int_0^{D^{(rx)}}\int_0^{\mathrm{SNR}_T} \frac{1}{\overline{\mathrm{SNR}(y)}} e^{-\frac{1}{\overline{\mathrm{SNR}(y)}}x} \frac{1}{D^{(rx)}}\mathrm{d}x\mathrm{d}y \\ &= \int_0^{D^{(rx)}}\int_0^{\mathrm{SNR}_T} \frac{y^\alpha N_0}{P_t K_0} e^{-\frac{y^\alpha N_0}{P_t K_0}x} \frac{1}{D^{(rx)}}\mathrm{d}x\mathrm{d}y \\ &= \frac{1}{D^{(rx)}}\int_0^{D^{(rx)}} 1 - e^{-\frac{y^\alpha N_0}{P_t K_0}\mathrm{SNR}_T}\mathrm{d}y, \end{aligned} \tag{24}$$

where P_t is the transmission power, $\overline{\mathrm{SNR}(y)}$ is the average SNR as a function of distance, and N_0 is the noise power. K_0 and α are a constant and an exponent corresponding to the path loss model, respectively. The PDF of the transmission distance, $f_d(y)$, is assumed to follow a uniform distribution, $d \sim \mathcal{U}(0, D^{(rx)})$.

Regardless of the fact that the linear combination may or may not contain an unwanted message, the receiver may fail to receive the transmission opportunities. Therefore, the event U is independent of the events F_1 and $\overline{F_2}$, and the second term in (19) is modeled as

$$\Pr[A_1, F_1, \overline{F_2}, U] = \Pr[A_1]\Pr[F_1, \overline{F_2}|A_1]\Pr[U|A_1]. \tag{25}$$

Using the argument in the calculation of (22),

$$\begin{aligned} \Pr[F_1, \overline{F_2}|A_1] &= \Pr[F_1|A_1] - \Pr[F_1, F_2|A_1] \\ &= p_e - p_e^2 - \rho p_e(1-p_e) \\ &= (1-\rho)p_e(1-p_e). \end{aligned} \tag{26}$$

The event $U|A_1$ is illustrated in Fig. 5 where VE2 transmits a linear combination to VE1. In this figure, if the transmitted linear combination includes any beacons from the VEs located outside of the VE1's receiving range $D^{(rx)}$, the linear combination is useless for VE1 and should be discarded due to lack of possibility of recovery. Given that VE2 only forwards the beacons in its forwarding queue to the VEs inside the feedback range, $D^{(nack)}$, the event $U|A_1$ happens if any VEs inside the VE2's feedback range fails to receive a beacon generated outside the VE1's receiving range, i.e., the crescent area in Fig. 5. There are two cases where VE2's forwarded linear combination does not include an unwanted message. First, VE2 itself fails to receive the beacon, and second, VE2 and all of VEs in VE2's feedback range receive it successfully. Assuming a linear road model and

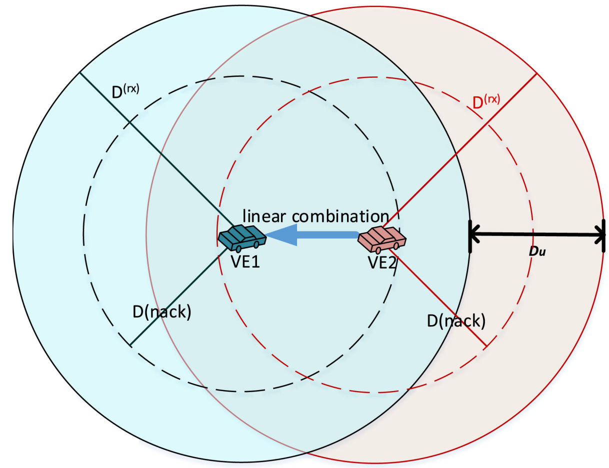


Fig. 5. Illustration of the event $U|A_1$.

a PPP for the topology of the VEs, the crescent area is simplified to the segment of $D_u = d$ in the figure, and $\Pr[U|A_1]$ is obtained as follows,

$$\Pr[U|A_1] = 1 - \sum_{k=0}^{\infty}\int_0^{D^{(rx)}}\left([\hat{p}_e + (1-\hat{p}_e)B(x)]^k f_{D_u}(x) \times \frac{(\lambda x)^k}{k!}e^{-\lambda x}\right)\mathrm{d}x, \tag{27}$$

where $B(x)$ is the probability that a beacon generated by a VE on a segment with length of x is successfully received by all VEs inside the VE2's feedback range. In other words, there will be no corresponding NACK for this beacon. $\hat{p}_e$ denotes the probability that VE2 fails to receive and recover the beacon sent from a VE on the segment of D_u, and thus it cannot further forward it to VE1. Since $\hat{p}_e$ is dependent on the VE2's current LoD, its derivation is not straightforward. However, it obviously is less than p_e since in the best case where the VE2's LoD is zero, $\hat{p}_e$ is equal to p_e, $\hat{p}_e = p_e$. Hence, we apply the approximation of $\hat{p}_e \approx p_e$. Underestimating $\hat{p}_e$ results in overestimation of $\Pr[U|A_1]$ and p_{-1}. A larger p_{-1} makes our theoretical analysis conservative. $f_{D_u}(x)$ represents the PDF of D_u. Assuming location of each VE is uniformly distributed and independent to other VEs' location, $f_{D_u}(x) = 1/D^{(rx)}$. Given a random point on segment D_u, d_u denotes the distance from this point to the right boundary of the receiving range of VE2 in Fig. 5.

$$B(D_u) = \sum_{k=0}^{\infty}\int_0^{D_u}\left(\frac{\left(\lambda\min\left[D^{(nack)} + d_u, 2D^{(nack)}\right]\right)^k}{k!} \times e^{-\lambda\min\left[D^{(nack)}+d_u, 2D^{(nack)}\right]} \times \left(1 - \tilde{p}_e(d_u, D_u)\right)^k \frac{1}{D_u}\right)\mathrm{d}d_u, \tag{28}$$

where $\tilde{p}_e(d_u, D_u)$ is the probability that a single VE within the feedback range of VE2 reports a NACK to the transmitted beacon from the segment of D_u as described in $B(D_u)$. Closed-form derivation of $\tilde{p}_e(d_u, D_u)$ is not straightforward due to its dependency on the VE's current LoD. $\tilde{p}_e(d_u, D_u)$ is function of the distance between a targeted communication pair which varies from 0 to $D^{(rx)}$. With the same argument on $\hat{p}_e \approx p_e$, we approximate $\tilde{p}_e(d_u, D_u)$ as $\tilde{p}_e(d_u, D_u) \approx p_e$. This approximation underestimates $\tilde{p}_e(d_u, D_u)$ and p_{-1}, and thus overestimates the performance when the vehicle density is small.

For the case that the segment's length is less than the feedback range, i.e., $0 \le d_u \le D_u \le D^{(nack)}$, (28) is derived as

$$B(D_u) = \sum_{k=0}^{\infty} \int_0^{D_u} \left(\frac{\lambda^k \left(D^{(nack)} + d_u\right)^k}{k!} e^{-\lambda\left(D^{(nack)}+d_u\right)} \times (1-p_e)^k \frac{1}{D_u} \right) \mathrm{d}d_u$$

$$= \sum_{k=0}^{\infty} \frac{(1-p_e)^k}{D_u} \int_{D^{(nack)}}^{D_u+D^{(nack)}} \frac{(\lambda x)^k}{k!} e^{-\lambda x} \mathrm{d}x$$

$$= \sum_{k=0}^{\infty} \frac{(1-p_e)^k}{D_u} \frac{1}{\lambda} \int_{D^{(nack)}}^{D_u+D^{(nack)}} \frac{\lambda^{k+1} x^k e^{-\lambda x}}{\Gamma(k+1)} \mathrm{d}x$$

$$= \sum_{k=0}^{\infty} \frac{(1-p_e)^k}{\lambda D_u \Gamma(k+1)} \left[\gamma\left(k+1, \lambda(D_u + D^{(nack)})\right) - \gamma\left(k+1, \lambda D^{(nack)}\right) \right], \quad (29)$$

where $\Gamma(\cdot)$ and $\gamma(\cdot,\cdot)$ are gamma function and lower incomplete gamma function, respectively.

Remark: We used p_e to approximate $\hat{p}_e$ and $\tilde{p}_e(d_u, D_u)$, which underestimates and overestimates the theoretical analysis, respectively. These approximations tend to underestimate theoretical analysis when the number of neighbors is small (small λ) and overestimate it otherwise.

2) p_1: It is defined as the probability that a receiver receives both the first transmission opportunity and the second one corresponding to a neighboring VE. According to the LoD modeled in Section IV-A, p_1 is meaningful only if a VE has missed at least one beacon. Therefore, p_1 is conditioned on a negative LoD. In other words, the event corresponding to p_1 happens if the receiver, VE1 in Fig. 5, is located within the feedback range of VE2. This probability is modeled as

$$\begin{aligned} p_1 &= \Pr[A_2, \overline{F}_1, \overline{F}_2, \overline{U}] \\ &= \Pr[A_2] \Pr[\overline{F}_1, \overline{F}_2 | A_2] \Pr[\overline{U} | A_2] \\ &= \Pr[A_2] \left[(1-p_e')^2 + \rho p_e' (1-p_e') \right] (1 - \Pr[U|A_2]), \end{aligned} \quad (30)$$

where A_2 denotes the event that the distance between the transmitter and the receiver is less than $D^{(nack)}$, i.e., $d \le D^{(nack)}$. Similar to the models in (20) and (23), we have

$$\Pr[A_2] \approx \min\left[\frac{2D^{(nack)}}{\mathbb{E}[D_s]}, 1 \right], \quad (31)$$

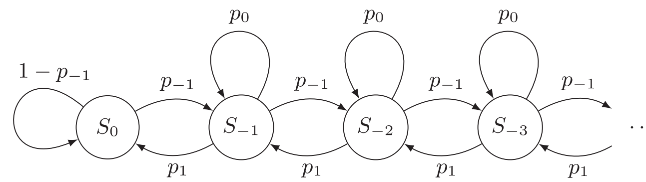


Fig. 6. Markov chain using a VE's LoD as states.

$$p_e' = \frac{1}{D^{(nack)}} \int_0^{D^{(nack)}} 1 - e^{-\frac{y^\alpha N_0}{P_t K_0} SNR_T} \mathrm{d}y. \quad (32)$$

Derivation of $\Pr[U|A_2]$ is similar to $\Pr[U|A_1]$ in (27) and it is given by

$$\Pr[U|A_2] = 1 - \sum_{k=0}^{\infty} \int_0^{D^{(nack)}} \left([p_e' + (1-p_e')B(x)]^k f_{D_u}'(x) \times \frac{(\lambda x)^k}{k!} e^{-\lambda x} \right) \mathrm{d}x, \quad (33)$$

where $f_{D_u}'(x) = 1/D^{(nack)}$. Accordingly, p_1 is derived from (30) by substituting $\Pr[A_2]$ and $\Pr[U|A_2]$ obtained in (31) and (33), respectively.

3) p_0: Since p_{-1} and p_1 have been derived already, derivation of p_0 is straightforward as follows.

$$p_0 = \begin{cases} 1 - p_{-1} - p_1, & LoD \ne 0, \\ 1 - p_{-1}, & LoD = 0. \end{cases}$$

C. Metrics

1) Beacons Recovery Delay (BRD): Assuming all of the VEs have received or recovered the previously sent beacons, i.e. LoD $= 0$ and according to (11) and the probabilities, p_1, p_0, and p_{-1}, derived in Section IV-B, the cumulative distribution function (CDF) of BRD is as follows,

$$F_{\mathrm{BRD}}(t) = \frac{\sum_{n=1}^{tN_c} P_N^0(n+1)}{\sum_{n=1}^{(N_t-1)N_c} P_N^0(n+1)}, \quad t = 1, 2, \ldots, N_t - 1, \quad (34)$$

where N_c and N_t are the total number of channels and the total number of time slots in a beaconing period, respectively. VEs in the neighbor list will stop forwarding and recovering a tagged VE's beacon message generated in the last period once the VE sends out a new beacon in the current period. In other words, the expiration time for the beacons is one beaconing period. Therefore, $F_{\mathrm{BRD}}(t)$ is conditioned on the missing beacons which are recoverable within a period.

2) Successful Deliver Ratio, η: In Fig. 6, a discrete-time Markov chain has been built using a single VE's LoD as the states. The probability of each state, S_{-r}, is given by

$$S_{-r} = \left(1 - \frac{p_{-1}}{p_1}\right)\left(\frac{p_{-1}}{p_1}\right)^r, \quad r = 0, 1, 2, 3, \ldots. \quad (35)$$

Regardless of the states, once $\overline{F_1}|A_1$ happens, the message is successfully delivered, since a VE always transmits its own beacon message on the first transmission opportunity. Otherwise,

TABLE I
VEs' PARAMETERS IN SUMO

Parameter	Value	Description
Maxspeed	$[80, 200]$	The maximum speed that a VE will travel (km/h)
Length	$[2.2, 12]$	The length of a VE (m)
Accel	$[2, 5]$	The acceleration ability of VEs $(\mathrm{m/s^2})$
Decel	$[3, 8]$	The deceleration ability of VEs $(\mathrm{m/s^2})$
Mingap	$[2, 5]$	The offset to the leading VE when standing in a jam (m)
Sigma	$[0.2, 0.7]$	The VE's driver imperfection (between 0 and 1)
Car-following model	*Krauss*	The model describing how a VE follows another one
Lane-changing model	*LC2013*	The model describing how a driver changes a lane

the message may be recovered in time depending on the current state of LoD. We define the successful deliver ratio, η, from a VE's perspective. It is defined as the probability of successfully receiving or recovering a beacon sent by another VE in its neighbor list. Based on the derivations in Section IV-B, η is given as follows,

$$\begin{aligned}\eta = \; & \Pr[\overline{F_1}|A_1] + \Pr[F_1, \overline{F_2}, \overline{U}|A_1] \\ & \times \left[S_0 + \sum_{r=1}^{(N_t-1)N_c} \left(S_{-r} \sum_{n=r}^{(N_t-1)N_c} P_N^r(n) \right) \right] \\ & + \left(1 - \Pr[\overline{F_1}|A_1] - \Pr[F_1, \overline{F_2}, \overline{U}|A_1] \right) \\ & \times \left[\sum_{r=0}^{(N_t-2)N_c} \left(S_{-r} \sum_{n=r+1}^{(N_t-1)N_c} P_N^{r+1}(n) \right) \right], \qquad (36)\end{aligned}$$

where

$$\Pr[\overline{F_1}|A_1] = 1 - p_e,$$

$$\Pr[F_1, \overline{F_2}, \overline{U}|A_1] = \Pr[F_1, \overline{F_2}|A_1]\,(1 - \Pr[U|A_1]).$$

$\Pr[F_1, \overline{F_2}|A_1]$ and $\Pr[U|A_1]$ are obtained from (26) and (27), respectively.

V. PERFORMANCE EVALUATION

A. Network Settings

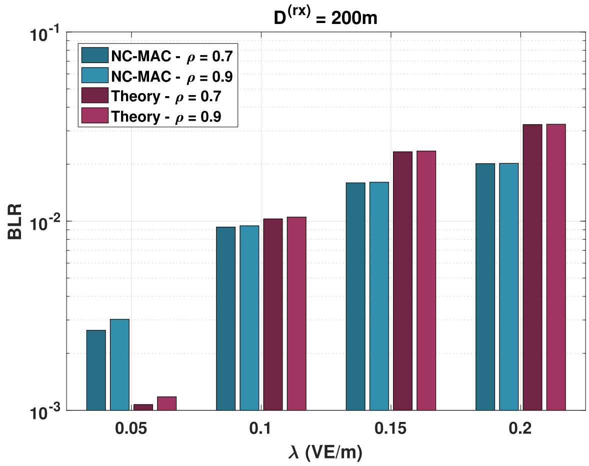
To investigate whether the proposed solution is reliable and scalable for beaconing in V2X, we conducted extensive simulations in three different scenarios: (I) a linear network, (II) highway scenario, and (III) urban scenario. In the linear network, we assume that the topology of VEs follows a one-dimension Poisson point process (PPP) and the VEs are moving in a single-lane road. For the highway and urban scenario, we used SUMO to generate traffic traces. SUMO is a microscopic traffic flow simulator which can generate real VE routes and simulate how traffic changes in a large road network. In the highway scenario, a bidirectional road 10 km is set where each direction contains four lanes with different speed limits, [60,80 100 120] km/h. In the urban scenario, there are two intersections where four bidirectional roads intersect. Each direction contains two lanes with different speed limits, [50,60] km/h. The length of each road is set to 2 km and the network's area is totally $6 \times 4,\ \mathrm{km}^2$. Traffic lights are set at each of the road segments at the intersections and the duration of green light is 25 s. Deployed VEs in both of the scenarios have different performance parameters such as length, acceleration, deceleration, and maximum speed from seven different types of VEs. In the trace generation, Krauss and LC2013 have been considered as car-following and lane-changing models, respectively. Driver imperfection has been considered in the traces as well. The attributes of VEs used in the SUMO are summarized in Table I. The VEs' performance parameters and destination are chosen randomly when they enter the simulation system, and they leave the system when they reach the chosen destination.

TABLE II
PARAMETER SETTINGS

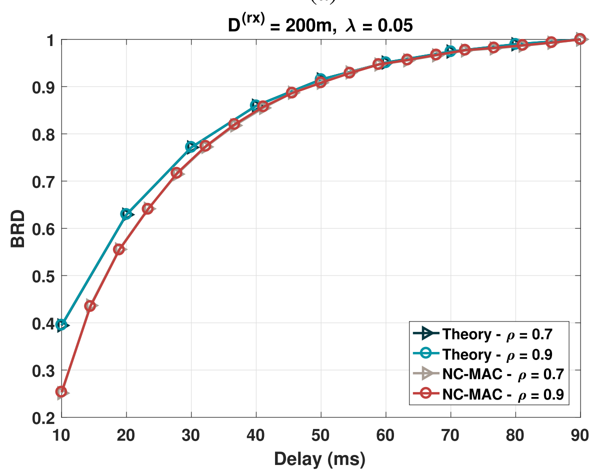
Parameters	Value	Description
L	2 (km)	Road length
λ	$[0.05, 0.3]$ (VE/m)	VEs density
$D^{(rx)}$	200, 250 (m)	Beacon receiving range
$D^{(nack)}$	150 (m)	Feedback range
N_s	50	Number of resource blocks
N_c	5	Number of channels
T_p	100 (ms)	Beaconing period
K_0	$10^{-4.38}$ [38]	Path loss constant
α	3.68	Path loss exponent
P_t	250 (mW)	Transmission power
SNR_T	3.3 dB [39]	Decoding SNR threshold
W	180×6 KHz	Channel bandwidth
N_0	$W \times 10^{-17.4}$ (mW)	Noise power
ρ	0.5, 0.7, 0.9	Correlation factor

B. Communication Setup

For wireless channels, we apply the line of sight device-to-device communication path loss model and Rayleigh fading. Parameters are summarized in Table II. In the simulations, we assume that each VE has acquired a resource block before starting the beaconing process. Each VE will generate beacons periodically, and they expire after a period. The target receivers of a tagged VE are all of the VEs in the broadcasting range of the transmitter. For comparison, we also simulated the cases using LTE mode–4 (C–V2X) MAC [39]. We assume that the VEs using C–V2X have already made a reservation and thus, they can start the beaconing process based on fixed orthogonal semi-persistent scheduling patterns (every 100 ms) without any collisions. Note that this assumption exaggerates C–V2X's performance as it suffers badly from the hidden terminal problem. C–V2X does



(a)



(b)

Fig. 7. Comparison of NC–MAC results and theoretical derivations. There is no limitation on the VEs' forwarding queue size. (a) Beacon loss ratio. (b) Beacon recovery delay.

not utilize any feedback mechanism and it always transmits a beacon message twice during each allocated resource block.

C. Simulation Results

We compare the beacon loss ratio (BLR) between NC–MAC protocol and C–V2X. The BLR is defined as

$$\mathrm{BLR} = 1 - \frac{\#\text{ of received beacons}}{\#\text{ of expected beacons to be received}} = 1 - \eta. \tag{37}$$

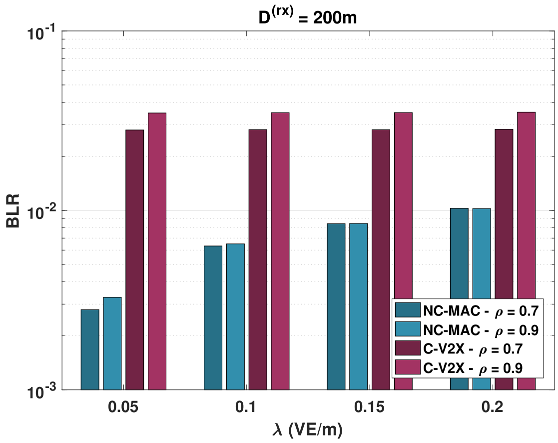
The CDF of BRD according to (34) is compared with the results from simulations.

Figs. 7 (a) and (b) depict the BLR and BRD of NC–MAC compared to the theoretical derivation in (34) and (35) where $D^{(rx)} = 200$ m, $\lambda = [0.05,\ 0.2]$ VE/m, and $\rho = 0.7, 0.9$. The correlation factor, ρ, measures how the temporal correlation affects two successive transmission opportunities in each resource block for a VE. The results are from a one-dimension linear network and there is no limitation on the number of linear combinations in a VE's forwarding queue. As it can be observed from Figs. 7 (a) and (b), the results from theoretical analysis for both BLR and BRD generally agree with NC–MAC simulation. It should be noted that the analysis slightly underestimates the BLR when λ is small, and it overestimates it when λ is large. This is due to the probability simplification in the derivations as discussed in Section IV.

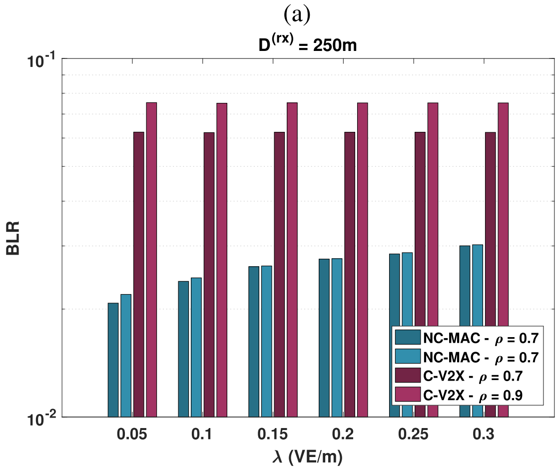
The performance of C–V2X and NC–MAC are compared in Figs. 8. As shown in Fig. 8 (a), NC–MAC achieves a significant gain compared to C–V2X when the beaconing range is fixed to 200, 250 m. The BLR is reduced from 3% to around 0.3% and 1% for $\lambda = 0.05$ and $\lambda = 0.2$, respectively. The results show approximately about 75% of the missed beacons in C–V2X can be recovered by NC–MAC protocol. The proposed NC–MAC has a BLR of 1% in dense scenarios ($\lambda = 0.15$ and $\lambda = 0.2$), implying that NC–MAC is reliable and scalable compared to C–V2X. In Fig. 8 (b), although the BLR degrades compared to Fig. 8 (a) where $D^{(rx)} = 200$ m, the performance gain of NC–MAC protocol is still substantial and NC–MAC can recover approximately 65% more beacons. The observable degradation in Fig. 8 (b) is because a larger number of neighbors increases the probability of receiving linear combinations containing unwanted beacons, which may be useless in the recovery process of missed beacons. These results are useful to identify the applicable scenarios for the proposed protocol. The channel correlation factor, ρ, does not dramatically affect the results. All the schemes receive slightly better performances given a smaller ρ because of the time diversity gain.

In Fig. 8 (c), the CDF of the BRD for NC–MAC in different scenarios is given. The results in this figure were obtained according to the beacons missed by at least a VE. The VE density, broadcasting ranges, and correlation factors are set to $\lambda = 0.1$ (VE/m), $D^{(rx)} = 200,\ 250$ m, and $\rho = [0.7,\ 0.9]$, respectively. The size of the VEs' forwarding queue is 11. Fig. 8 (c) shows that the CDF of the BRD for a larger broadcasting range is higher than the smaller one. In other words, by increasing the broadcasting range in NC–MAC protocol, there would be a higher chance of beacons recovery with a smaller delay, which validates our expectation. Moreover, Fig. 8 (c) shows that among the recovered beacons in a beaconing period, a missed beacon can be recovered with probability of 90% within half of a period. Note that beacons expire after generation of a new beacon.

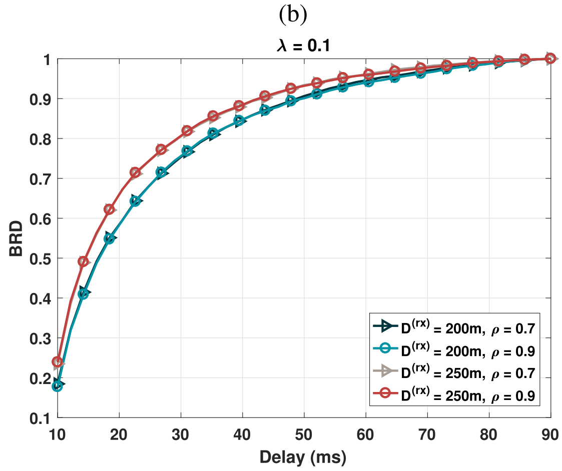
Fig. 9 shows the impact of the forwarding queue size on BLR for different VE densities. As it was mentioned earlier, linear combinations of beacons play an important role in NC–MAC performance. Fig. 9 implies that there is an optimum size for the forwarding queue. In other words, forwarding all of the requested beacons in the transmission opportunity may not lead to the lowest BLR. The reason is that any VE can recover a missed beacon only during one beaconing period, and by combining more beacons in a linear combination, the VE needs more linear combinations to generate a full-rank matrix to be able to recover the missed beacons. Note that by increasing the queue size, the BLR will approach to the results in Fig. 7 where there is no limitation on the queue size. It is remarkable that there is a queue size where the BLR for different VE densities intersect. It can be a key factor for the scenarios



(a)



(b)



(c)

Fig. 8. Comparison of NC–MAC with C–V2X in terms of BLR and BRD. The size of forwarding queue in NC–MAC is set to $F_s = 11$ in this case.

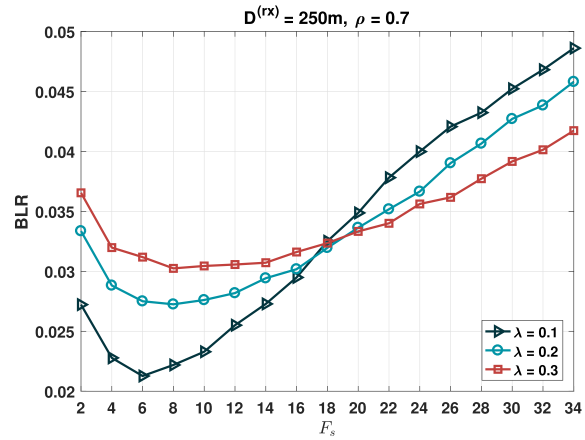
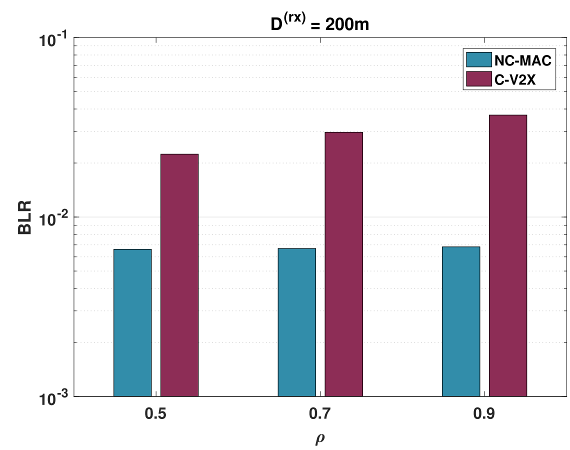
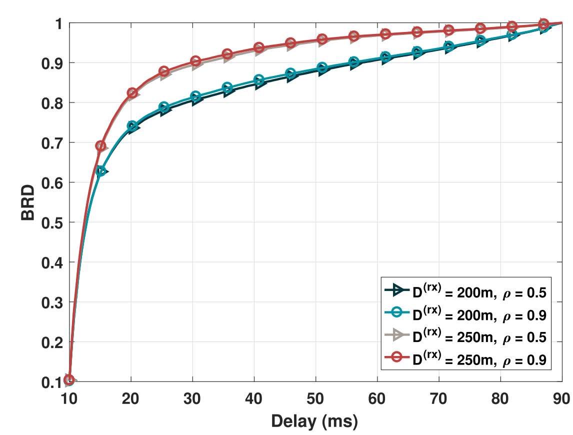


Fig. 9. Comparison of the BLR corresponding to different VE densities with respect to the VE's forwarding queue size.



(a)

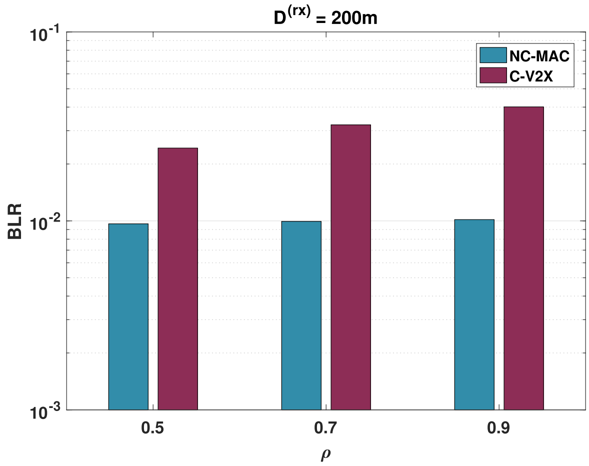


(b)

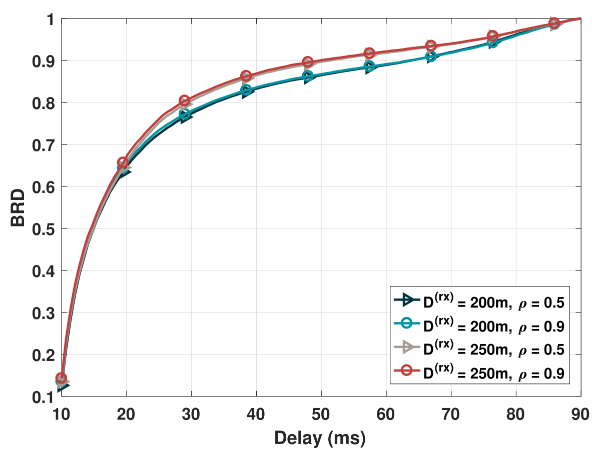
Fig. 10. BLR and BRD of NC–MAC and C–V2X in the highway scenario. The forwarding queue size is set to 10 in this case.

where VE density changes and maintaining the BLR is of high importance.

Fig. 10 and Fig. 11 show the BLR and BRD results corresponding to the highway and urban scenarios, respectively, whose topology setup were explained earlier in this Section. The forwarding queue size is set to $F_s = 10$ in the simulation. These figures are in good agreement with the results in Fig. 8 (a). According to these results, in both highway and urban real scenarios, the proposed NC–MAC can recover around 70% of the missed beacons compared to C–V2X. In terms of BRD, more than 80% of the missed beacons in one beaconing period can be recovered in half of period in both scenarios. Compared to the highway scenario, the BLR and BRD are larger and smaller, respectively in the urban scenario despite the similar



(a)



(b)

Fig. 11. BLR and BRD of NC–MAC and C–V2X in the urban scenario. The forwarding queue size is set to $F_s = 10$ in this case.

number of VEs in the networks. It is due to the higher VE density in the traffic congestion of the intersections, while in the highway scenario, the VE density is roughly the same all over the road. According to this figures, a higher correlation between the transmission opportunities, ρ, increases the BLR slightly due to higher probability of two successive drop. Fig. 10 and Fig. 11 verify that NC–MAC is more reliable and scalable, and can achieve significant performance gain in practical scenarios compared to C–V2X.

VI. Conclusion

In this paper, we proposed a novel distributed protocol to improve the beacon transmission reliability in VANETs. The current solutions for V2X communications, DSRC and C–V2X, cannot support a reliable and scalable beacon broadcasting process. The former suffers from performance degradation in dense scenarios due to its contention-based medium access protocol, and in the latter beacon collision is inevitable and it does not exploit any HARQ feedback mechanism.

To address these issues, we combined a preamble-based feedback mechanism, beacon retransmission, and the network coding together to enhance the communication reliability. A complete protocol design, including forwarding operation and feedback, has been shown. Extensive simulations and numerical evaluations have been given to show the performance gain of NC–MAC protocol over the conventional C–V2X. We evaluated the protocol in urban and highway traffic scenarios, generated by SUMO. Compared to C–V2X, NC–MAC protocol can achieve significant performance gains in the simulation scenarios.

The current protocol design only supports one-hop transmission. Even though the reliability has been improved, the broadcasting range remains the same. How to incorporate the multi-hop transmissions in the proposed protocol requires further investigations. In this paper, the target receivers are not selected, i.e., all the VEs in the broadcasting range can receive and further forward the beacons. This design may loss performance gain in superdense scenarios due to the reason that a higher density results a higher probability of receiving linear combinations containing unwanted beacons. A dynamic grouping mechanism may help to control the target receivers and forwarding operations.

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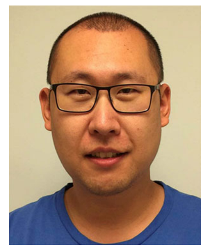

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