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Reliable and Enhanced Cooperative Cross-layer Medium Access Control Scheme for Vehicular Communication

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Abstract: In an unreliable cluster-based, broadcast vehicular network setting, we investigate the transmission reliability and throughput performance of random network coding (RNC) as a function of the percentage of packet generation rate and transmit power to noise ratio. In the paper, a novel scheme called reliable and efficient cooperative cross-layer MAC (RECMAC) is proposed. The proposed scheme consists of a source vehicle broadcasting packets to a set of receivers (i.e. one-to-many) over independent broadcast erasure channels. The source vehicle performs RNC on N packets and broadcasts the encoded message to a set of receivers. In each hop, several vehicles form a cluster and cooperatively transmit the encoded or re-encoded packet. The combination of RNC, cluster based, and cooperative communications enables RECMAC to optimally minimize data redundancy, which means less overhead, and improve reliability as opposed to coding-based solutions. Theoretical analyses and simulation results show that under the same conditions RECMAC scheme can achieve improved performance in terms of transmission reliability and throughput.

1. Introduction

Vehicular networks have attracted a tremendous research attention in the recent years as a result of their widespread application areas, such as safety-related, commercial-oriented, and convenience-oriented applications [1-2]. Hence, with all these critical application areas, robustness and reliability are some of the intrinsic requirements of vehicular networks. Unfortunately, vehicular networks generally operate under harsh environment, in which wireless communication conditions are most times very complex. More so, the conventional architecture of wireless network communication which the nascent vehicular networks adopted is based on *store-and-forward* approach where all the packets received and or self-generated are briefly kept in the virtual buffers prior to onward forwarding to the next-hop with no further processing. This traditional approach not only proved to be spectrally inefficient but also adversely affects the performance as a result of incurred heavy network overhead especially as the load (i.e. percentage of packet generation rate) on the network increases.

The dynamic environment of Vehicular Ad-Hoc Networks (VANETs) often lead to possibility of losing data packets meant to deliver life-saving information, thereby making communication reliability a challenge. This challenge has been tackled with approaches like request-to-send/clear-to-send (RTS/CTS), broadcast-request-to-send/broadcast-clear-to-send (BRTS/BCTS), Automatic Repeat reQuest (ARQ) and acknowledgement/No-acknowledgement (ACK/N-ACK) [3]. However, these approaches can only work efficiently well with one-to-one, unicast communication as opposed to Internet of Vehicles (IoVs) where traffic safety depends on many one-to-many, broadcast communication scenarios. Unfortunately, message broadcast transmission may fail randomly at different receivers as a result of the known lossy nature of wireless channel.

However, since the conception of the idea of network coding (NC) [4], several studies have shown that RNC can asymptotically achieve both unicast and multicast capacity in a wireless network associated with error-prone wireless channels. NC has also been shown to aid broadcast transmission reliability through transmission error recovery with minimum message retransmission due to increase packet content [5] of each transmission. Several studies in information theory have shown that packet(s) routing alone is not sufficient to achieve maximum network throughput in the general model of communication networks [6]. NC techniques have been proposed for enhanced performance for both broadcast and multicast network traffic. It is a generalization of packet routing in which stations can generate enriched output data by encoding previously received packets. With bit-wise exclusive OR (XOR) coding technique, an encoded packet consists of the encoded data as well as the coding vector information. Hence, when a vehicle receives a coded packet, it knows the packets that are encoded together and how to decode the coded packet if it has at least one packet out of the list of the packets encoded together. Similar example of study is also shown in [7] where it is established that NC can improve the overall network throughput, which cannot otherwise be achieved through the traditional *store-and-forward* approach.

In this paper, a cluster based vehicular communication scheme is proposed, named reliable and efficient cooperative cross-layer MAC (RECMAC) scheme for vehicular communication based on RNC technique aiming at improving encoded message broadcast transmission reliability and maximum achievable throughput with low algorithmic complexity. In particular, RECMAC minimizes the number of packet retransmissions at the MAC layer by encoding several different packets into one packet through RNC at the source cluster before being broadcasted to the next-hop.

The rest of the paper is organized as follows. The review of the latest related studies is contained in Section II. Section III introduces a detailed description of RECMAC system model. Section IV contains the performance analysis of the proposed scheme. The simulation experiment is shown in Section V, and Section VI concludes the paper.

2. Literature Review

Recent studies on efficient application of NC over vehicular networks generally addressed the challenges of improving vehicular communication reliability and quality at the MAC layer. The authors in [8] proposed a medium access control (MAC) protocol for reliable transmission of time-critical packets in vehicular communication networks. The authors implemented a topology-transparent message broadcast by applying positive orthogonal codes (POC) to ensure time-sensitive message broadcast reliability in a dynamic vehicular communication environment. Fallah *et al.* [9] studied efficient message dissemination in cooperative vehicle safety systems (CVSS) by intensively analyzing two basic controllable parameters that affect vehicular network condition and overall performance such as the data transmission rate (frequency) and communication radio transmission range. The authors used the findings reached after analyzing the effects of different choices of data transmission rate and range to design robust feedback control schemes for efficient transmission range adaptation in VANETs. Similarly, the authors in [10] have proposed a vehicular cooperative MAC (VC-MAC) scheme, which exploits the potentials of V2V communication to increase the overall achievable system throughput by leveraging V2V message sharing for serving nodes which are beyond the RSU's radio service coverage.

Interestingly, sizable number of works have investigated the potentials of applying network coding for enhanced performance in mobile wireless broadcast communication systems [11-12], nevertheless, none of them is specifically designed with full consideration of the peculiar characteristics of vehicular networks. Some other studies have investigated the performance impacts of network coding on vehicular networks. Li *et al.* [13] studied how to maximize popular content distribution (PCD), which is one of the basic services offered by vehicular networks, by applying network coding concept. In their study, a push-dependent PCD scheme called CodeOn is introduced, where contents are actively broadcasted to vehicles from road side Access Points (APs), and further distributed amongst vehicles with the aid of cooperative VANETs. In the proposed CodeOn, the authors employ a symbol level network coding (SLNC) technique to combat the lossy wireless transmissions and improve content transmission reliability. Wu *et al.* [14] addressed the challenges of designing an efficient data dissemination protocol for vehicular networks caused by high vehicle mobility, error-prone characteristics of wireless communication, and the limited wireless resources. The protocol employs network coding to minimize protocol overhead and improve packet reception probability.

Amongst the few existing studies that have incorporated network coding into vehicular networks to improve transmission reliability and enhance performance, the study conducted by Hassanabadi and Valaee [15] directly falls in the category of the RECMAC scheme proposed in this paper. The authors designed a scheme that uses rebroadcasting of network coded safety packets to significantly improve the overall reliability of data dissemination. Although, the scheme the authors designed provides transmission reliability for small safety packets with low overhead, large and saturated network scenario will undeniably incur heavy network overhead. Such heavy overhead can become a serious drawback due to ensuing excessive channel congestion, which can produce high rate of packet collisions, as well as lead to unacceptable reliability challenges especially for safety applications. In this paper, we resolved this issue by combining RNC with vehicle clustering technique to divide large and dense network into different separate manageable vehicle clusters primarily for boosting performance by maintaining low network overhead while RNC leads to high transmission reliability and maximizes the total achievable network throughput. Few studies also applied deterministic NC to improve transmission reliability [16-17]. Furthermore, vehicle clustering technique is a crucial network management task for vehicular communication networks to resolve even the challenge of broadcast storm and to cope with the rapidly changing topology, which is very common in vehicular networks. Although, the issue of maximizing the overall achievable network throughput and improving reliability of conventional wireless transmission have been hugely studied in the network community, many unique characteristics of the VANET bring out new research challenges.

3. System Model

With the developed algorithm of our proposed RECMAC protocol, packets transmission is cluster-based, where each cluster is composed of N mobile stations as is demonstrated in Fig. 1. The model is built on the assumption that the network is saturated with the source mobile station having packets to broadcast to destination vehicle with the intention that other members of the source cluster will overhear the broadcasted messages.

4.2 RECMAC Scheme Algorithm

The proposed RECMAC Scheme algorithm consists of two stages such as *packets encoding at the cluster head (CH) of the source cluster*, and *packets decoding at the destination node*. It is noteworthy to mention that all vehicles maintain a virtual packet pool (or a virtual buffer),

$(\mathcal{P} \in \mathbb{N}) = (P_1, P_2, P_3, \cdots, P_{\mathbb{M}})^{\mathbb{T}}$, where $\mathbb{M}$ denotes the total number of self-generated and received packets from other vehicles within the last $\mathbb{T}$ (ms). Prior to packets coding, the source vehicle generates a matrix of $1 \times \mathbb{M}$ encoding vector, $\mathbb{V}$,

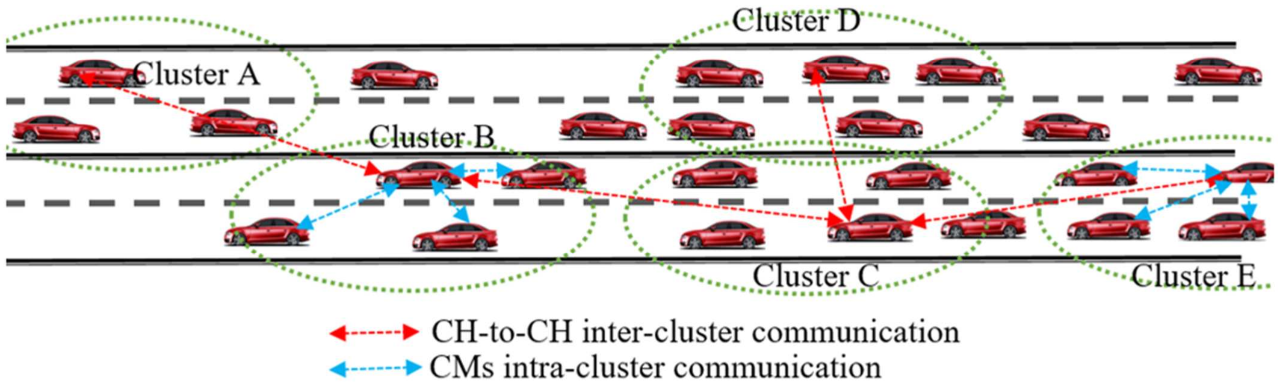

Fig. 1. *A typical vehicular clustering system model*

which is randomly computed over the Galois Field, $(GF(q)$. Then, random network coding is used to encode both the native and the received packets $\mathcal{P}$ contained the virtual buffer as

$$\mathbb{C} = (P_1, P_2, P_3, \cdots, P_{\mathbb{M}})^{\mathbb{T}} \cdot \mathbb{V} \qquad (1)$$

Firstly, the source vehicle makes single-hop broadcast of the coded data packets $\mathbb{C}$ to the cluster members (CMs). The encapsulation formation of the encoded data packets $\mathbb{C}$, and encoding vector $\mathbb{V}$ into one frame is depicted in the diagram shown in Fig. 2. Since all the nodes within the source cluster (i.e., the CMs) are all in radio communication range of one another, it is guaranteed that all the vehicles around the immediate zone of interest (ZoI, i.e. the zone where a traffic emergency has ensued) will receive the broadcast transmission from the source vehicle provided that the pre-set threshold (SNR_0) is less than the received signal-to-noise-ratio (SNR). In order to avoid transmission collision, only the CH has the privilege of replying the source vehicle with a CTB and an ACK frame to acknowledge the successful reception of the broadcasted encoded data packets $\mathbb{C}$ by the source vehicle.

Secondly, the CH of the source cluster employs the same concept of random network coding to increase the capacity of the retransmission of the broadcasted encoded emergency messages. The CH increases the capacity by re-encoding the received encoded emergency messages with its own self-generated native packet as well as the packets received from other vehicles within the last $\mathbb{T}$ (ms) in order to widen the transmission coverage of the safety messages. In essence, the retransmission concept allows the vehicles beyond single-hop broadcast transmission of the source vehicle to receive the emergency messages and take action with respect to the ZoI. This procedure continues with the rest of the intermediate CHs in the same manner, until the broadcasted encoded emergency messages are delivered to the clusters within n-hop broadcast transmission from the ZoI (where $n \ngtr 4$). Now, let $\mathcal{P}_{\mathbb{C}} = \left(P_{\mathbb{C}_1}, P_{\mathbb{C}_2}, P_{\mathbb{C}_3}, \mathbb{C}\cdots, P_{\mathbb{C}_N}\right)^{\mathbb{T}}$ denote the total number of packets from the last single-hop broadcast transmission, so that $\mathbb{C}_{R_k}$ and $\mathbb{V}_{R_k}$ are the resultant encoded data packets and encoding vector, respectively, which are contained in $\mathcal{P}_{\mathbb{C}_k} | \, k = 1, 2, 3, \cdots, N$. Hence, each CH embarking on retransmission of the broadcasted emergency messages will randomly generate $\alpha_1, \alpha_2, \alpha_3, \cdots, \alpha_N$ encoding coefficients over $GF(q)$ to be able to re-encode the received packets with its own self-generated raw packets as

$$\mathbb{C}_i = \sum_{k=1}^{n} \mathbb{C}_{R_k} \cdot \alpha_k \qquad (2)$$

$$\mathbb{V}_i = \sum_{k=1}^{n} \mathbb{V}_{R_k} \cdot \alpha_k \qquad (3)$$

where $\mathbb{C}_i$ is the new re-encoded data (i.e. the combination of originally broadcasted encoded emergency messages $\mathbb{C}$ from the source vehicle and the new packets contained in the virtual buffer of the CH), and $\mathbb{V}_i$ denotes the corresponding re-encoding vector. The processes involved in the re-encapsulation and re-encoding of $\mathbb{C}$ and the new packets is shown in Fig. 3.

Since the RECMAC scheme uses broadcast transmission technique, high rate of both the encoded $\mathbb{C}$ and re-encoded $\mathbb{C}_i$ data packets redundancy across the clusters/network will definitely be inevitable. In order to resolve this high rate of data packets redundancy, each $\mathbb{C}$ and $\mathbb{C}_i$ are given unique sequence number, *SeqNum*. Hence, with the aid of *SeqNum*, duplicates of $\mathbb{C}$ and $\mathbb{C}_i$ are automatically deleted by the receiving vehicles before the process of decoding is initialised.

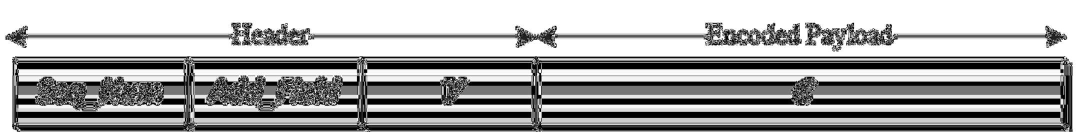

Fig. 2. *Encoded packet frame structure*

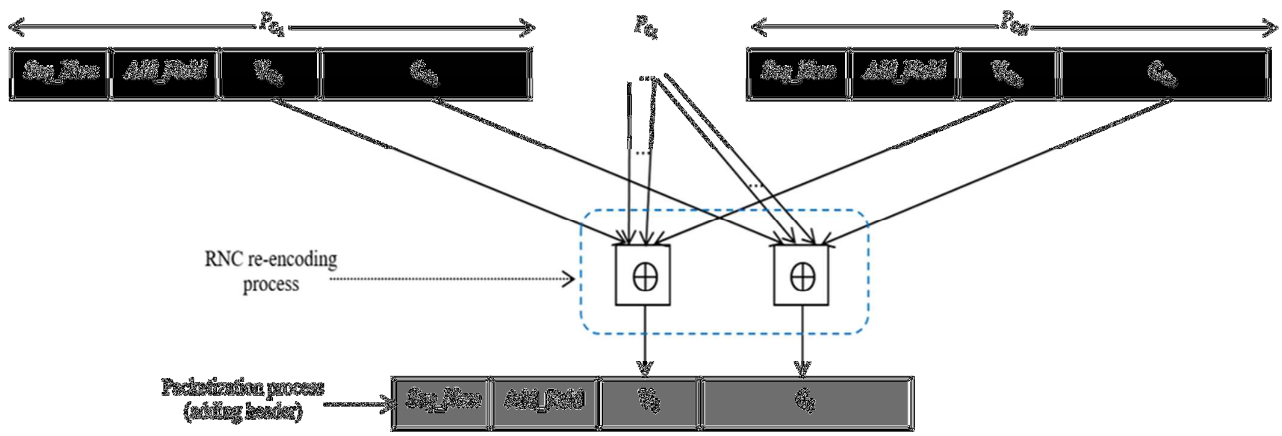

Fig. 3. *Packets encoding and re-encoding process*

Decoding at the receiving vehicle: Upon achieving the data packets redundancy control through the use of each encoded and re-encoded messages' sequence number (*SeqNum*), the recipient vehicles eventually initiate data decoding. Let us assume that N number of re-encoded data packets (i.e. $\mathbb{C}_i = \left(\mathbb{C}_{i_1}, \mathbb{C}_{i_2}, \mathbb{C}_{i_3}, \cdots, \mathbb{C}_{i_N}\right)$ has been received; then, the corresponding re-encoding matrix can be expressed as

$$\mathbb{V}_i = \left(\mathbb{V}_{i_1}, \mathbb{V}_{i_2}, \mathbb{V}_{i_3}, \cdots, \mathbb{V}_{i_N}\right)^T = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \cdots & \alpha_{1\mathbb{M}} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \cdots & \alpha_{2\mathbb{M}} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \cdots & \alpha_{3\mathbb{M}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha_{N1} & \alpha_{N2} & \alpha_{N3} & \cdots & \alpha_{N\mathbb{M}} \end{bmatrix} \qquad (4)$$

Hence, from Eq. (1), it follows that the correlation between the original blocks of individual packets and the received encoded packets could be expressed as

$$\mathbb{C}_i = \mathbb{P} \cdot \mathbb{V}_i \qquad (5)$$

So that the original packets $\mathbb{P} = (P_1, P_2, P_3, \cdots, P_{\mathbb{M}})$ can be successfully decoded and recovered through the application of Gaussian elimination method if $rank(\mathbb{V}_i) = \mathbb{M}$.

4.2 Vehicular Cluster Formation

Vehicular clustering is the process of subdividing the vehicular network into small manageable, coordinated groups to improve transmission reliability (i.e. boost performance) and minimize the network overhead. Some algorithms have been proposed for vehicular clustering, which takes into consideration the special characteristics of vehicular networks [18-19]. In this article, we developed an algorithm for efficient vehicular cluster formation based on the vehicles' location and direction of movement. Our developed algorithm uses the Euclidean distance to segment the network into smaller groups (i.e. clusters) of vehicles. In order to maintain stability in the life cycle of the vehicular clusters, the algorithm considers each vehicles' direction of movement. In order words, our proposed vehicular cluster formation algorithm only allows vehicles that are moving in the same direction to be members of the same cluster. If the direction is not taken into account in a highway environment with two ways, the vehicles that are moving in opposite direction to the cluster head will only be part of the cluster for a very short time, and a new cluster will have to be formed almost immediately. Considering the specified IEEE 802.11p standard (dedicated short-range communication (DSRC) radio) transmission range of 1km for a freeway [20] such as highway road scenario without buildings and with the aid of the Euclidean distance, the algorithm decides amongst requesting vehicles the ones that can be grouped and accepted as members of the same cluster. Each vehicle broadcasts its current kinematics information such as location, speed and direction of movement to create awareness of its presence to every neighbouring vehicle within its one-hop transmission. Finally, the cluster formation algorithm uses these kinematic details to segment the whole vehicular network into separate, manageable clusters.

4.2 Cluster Head Selection

With the aid of the received kinematics information broadcasted by different vehicles, each node builds its own one-hop neighbouring vehicles list. Vehicle j can be successfully selected as the CH, if and only if, vehicle j has the maximum number of one-hop neighbouring vehicles list, closest relative speed with respect to the average speed, and minimum average distance to the other vehicles in one-hop neighbouring list. Finally, based on these three conditions, the most suitably qualified candidate will be selected to be the CH based on the following cluster leader selection metric.

$$\mathcal{F}(j) = a\left(\sum_{k\in\mathbb{N}(j)} d(D_j, D_k)\right)\Big/ N_j + b\left(\sum_{k\in\mathbb{N}(j)} |\Delta\mathcal{V}|\right)\Big/ N_j - (c\cdot N_j) \quad (6)$$

Where

$$d(D_j, D_k) = d(D_k, D_j) = = \sqrt{(D_{k1}-D_{j1})^2 + (D_{k2}-D_{j2})^2 + \cdots + (D_{kn}-D_{jn})^2} = \sqrt{\sum_{k=1,j=1}^{n} (D_k - D_j)^2} \quad (7)$$

denotes the Euclidean distance between vehicles k and j; N_j represents the total number of vehicles within one-hop transmission range of vehicle j; $|\Delta\mathcal{V}| = |\mathcal{V}_k - \mathcal{V}_j|$ is the vehicular velocity difference between vehicles k and j; a, b, c are weight factors, with $a + b + c = 1$; and $\mathbb{N}(j)$ is the set of one-hop neighbouring vehicles to vehicle j.

Based on Eq. (6), the vehicle with the minimum value of the CH selection metric, $\mathcal{F}(j)$ will eventually be selected as the clusters' CH, and every other vehicle within one-hop transmission range of the selected CH automatically becomes cluster members (CMs). Consequently, these CMs are not allowed to participate in or initiate any further CH selection process unless the currently selected CH leaves the cluster or becomes unresponsive (i.e. dead node). In other words, the CMs and CH are different from one another as shown in Eq. (8) below

$$\begin{cases} CM = \langle k, \forall k \in \mathbb{N}(j) \ and \ k \neq j \rangle \\ CH = \langle j | \mathcal{F}(j) = Min(\mathcal{F}(k), \forall k \in \mathbb{N}(j)) \rangle \end{cases} \quad (8)$$

3.4 Cluster Head Selection

In order to accept a new CM into the cluster, a three-way handshake is initiated and completed between the new vehicle and the CH. First and foremost, the successfully selected CH periodically broadcast short beacons called *invite-to-join* (ITJ) packets to all the neighbouring vehicles within one-hop transmission range. The short ITJ beacons contain the CH direction of movement information to enable the receiving vehicle to decide whether it is allowed to join or not. This is because vehicles moving in opposite direction are not permitted by the developed algorithm to join clusters moving in a different direction to them so as to ensure cluster stability and durability. When a vehicle that is not currently a member of the cluster receive the ITJ beacon, it will check the direction of movement of the cluster (i.e. CH) and if it tallies with its own direction of movement, then the vehicle will respond with a similar short packet called *request-to-join* (RTJ) packet. Finally, the CH upon receiving an RTJ message will reply with an acceptance (or ACK) message to the vehicle if actually their direction of movement is the same. Consequently, the vehicle then becomes an active member to the cluster.

When a CH is departing from a cluster, it first relinquishes the cluster leader responsibility to the most closely located vehicle to itself. The handing over of leadership responsibility to another CM to automatically become the CH serves to: 1) keep the cluster coordinated as a one-hop transmission range network under a new CH without re-initiating the procedure of CH selection, since the closest node to the current CH will definitely have the minimum value of $\mathcal{F}(j)$ which is required to be successfully selected as a CH; 2) avoid incurring an extra network overhead which arises from the use of the CH re-selection algorithm when the CH leaves the cluster and a new CH is re-selected with the aid of the cluster leader selection discussed in Section 3.3.

4. Performance Analysis

4.1 Network Throughput Analysis

In Fig. 1, there are two distinct stages of message disseminations. Firstly, within the source cluster, the source vehicle broadcasts the encoded message to the CMs. Secondly, as discussed in Section 3.4, only the CH acknowledges the receipt of the broadcast from the source vehicle with an ACK frame and re-encodes the coded messages $\mathbb{C}$ with its own self-generated raw packets as well as the received packets from other vehicles within the last $\mathbb{T}$ (ms), if any, and rebroadcasts the re-encoded message to CHs of the neighboring clusters. Hence, let the probability of successful transmission of the encoded and re-encoded messages be denoted with P_s. The proposed RECMAC scheme's probability of successful transmission analysis is derived under a narrowband Rayleigh block fading channel based on theorem 1 below.

Theorem 1: *In a narrowband Rayleigh block fading vehicular communication link, with vehicles broadcasting packets at probability* p *using equal power levels, the probability of successful packet transmission assuming a desired source cluster sender-receiver CMs distance* d_0 *and* k *number of other CHs belonging to neighbouring clusters at distances* $d_i | i = 1, 2, \cdots, k, i \neq (k/2)$ *can be expressed as*

$$P_s(SNIR \geq \Theta) = exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right) \cdot \prod_{i=1, i\neq(k/2)}^{k} \left(1 - \frac{2\Theta p}{R_i^{\alpha} + 2\Theta}\right) \quad (9)$$

where Θ denotes a given SINR threshold which is based on the communication device and the adopted coding and modulation scheme, N_0 represents noise power, P_0 denotes the transmit power, d_0 is the distance between the source vehicle and the destination vehicles, α denotes the path loss exponent, $R_i = d_i/d_0$. The proof of theorem 1 is shown in Appendix 1.

Obviously, the overall achievable throughput in a large, saturated wireless network is generally constrained by the level of interference experienced across the network. Therefore, focusing on the interference part under the assumption that $N_0 = 0$, we determined the bounds that are basic, such that will not be exceeded even with an unconstrained transmit power using the following corollary.

Corollary 1: *With unit transmit power $P_i = 1$ and $N_0 = 0$ and under similar assumptions as in Theorem 1, the probability of successful packet transmission under a desired communication channel of a normalized distance, $R_0 = d_0/d_0 = 1$, and k number of other CHs belonging to neighbouring clusters at normalized distances $R_i = d_i/d_0 \,|i = 1, 2, \cdots, k, i \neq (k/2)$ can be expressed as*

$$P_s(SIR \geq \Theta) = \prod_{i=1, i\neq(k/2)}^{k} \left(1 - \frac{p}{\left(\frac{R_i^{\alpha}}{\Theta} + 1\right)}\right) = L_I(\Theta) \quad (10)$$

where $L_I(\Theta)$ represents the interference level I's Laplace transform, which is estimated at the stipulated signal-to-interference-ratio threshold Θ. The proof of corollary 1 is shown in Appendix 2.

Our analysis is based on the assumption that the locations of the vehicles represent a Poisson point process (PPP), with the distance between the source vehicle, CMs of the source cluster and other destination clusters fixed and there are k other vehicles constituting the 2-dimensional PPP. Although Eq. (10) gives the probability of successful transmission based on normalized vehicle distances $R_0 = d_0/d_0 = 1$ and k other CHs belonging to neighbouring clusters at normalized distances $R_i = d_i/d_0$, here, we find the joint density of $d_1, d_2, d_3, \cdots, d_k$, that is, normalized distances. Apparently, for one-dimensional PPP with density γ, the normalised distance from vehicles to their intended receivers creates the arrival times of a PPP. Therefore, the inter-arrival intervals are independent and identically distributed (i.i.d.) exponential with density γ as:

$$f_{d_i - d_{(i-1)}}\left(\beta_i - \beta_{(i-1)}\right) = \gamma e^{-\gamma(\beta_i - \beta_{(i-1)})}. \quad (11)$$

Accordingly, in the case of normalized distance $0 \leq d_1 \leq d_2 \leq d_3 \leq \cdots \leq d_k$, the composite density function of the inter-arrival intervals becomes

$$\begin{aligned} &f_{d_1, d_2, \cdots, d_k}(\beta_1, \beta_2, \cdots, \beta_k) \\ &= f_{d_1, d_2, \cdots, d_k - d_{(k-1)}}(\beta_1, \beta_2, \cdots, \beta_k - \beta_{(k-1)}) \\ &= \left(\gamma e^{-\gamma\beta_1}\right)\left(\gamma e^{-\gamma(\beta_2 - \beta_1)}\right) \cdots \left(\gamma e^{-\gamma(\beta_k - \beta_{(k-1)})}\right) \\ &= \gamma^k e^{-\gamma\beta_k}, \quad 0 \leq \beta_1 \leq \beta_2 \leq \beta_3 \leq \cdots \leq \beta_k. \quad (12) \end{aligned}$$

On the other hand, when vehicles are randomly distributed in accordance with a 2-dimensional PPP of density γ, the squared normalized distances from the intended receivers, according to [21], maintain the same distribution as the arrival periods of a PPP with density $\gamma\pi$. Similarly, from [22], we have

$$f_{d_i^2 - d_{(i-1)}^2}\left(\beta_i - \beta_{(i-1)}\right) = \gamma\pi e^{-\gamma\pi(\beta_i - \beta_{(i-1)})}, \quad (13)$$

Consequently, the squared normalized distances have a composite distribution with density

$$f_{d_1^2, d_2^2, \cdots, d_k^2}(\beta_1, \beta_2, \cdots, \beta_k) = (\gamma\pi)^k e^{-\gamma\pi\beta_k}, \quad 0 \leq \beta_1 \leq \beta_2 \leq \beta_3 \leq \cdots \leq \beta_k. \quad (14)$$

Finally, from Eq. (10), we can re-write the conditional success probability as

$$P_s(SIR \geq \Theta) = \prod_{i=1, i\neq(k/2)}^{k} \frac{\Theta d_0^{\alpha}(1-p) + (d_i^2)^{\alpha/2}}{\Theta d_0^{\alpha} + (d_i^2)^{\alpha/2}} \quad (15)$$

By integrating Eq. (15) w.r.t. the composite density in Eq. (14) with $\alpha = 3$ gives us

$$\begin{aligned} &P_s(SIR \geq \Theta) \\ &= \int_0^{\infty} \left((\gamma\pi)^k e^{-\gamma\pi\beta_k}\right) \\ &\cdot \int_0^{\beta_k} \cdots \int_0^{\beta_2} \prod_{i=1, i\neq(k/2)}^{k} \frac{\Theta d_0^3(1-p) + \beta_i^2}{\Theta d_0^3 + \beta_i^2} d\beta_1 \cdots d\beta_{(k-1)} \end{aligned} \quad (16)$$

Through the application of a related inductive technique as was used in [21], it can be shown that

$$\begin{aligned} &\int_0^{\beta_k} \cdots \int_0^{\beta_2} \prod_{i=1, i\neq(k/2)}^{k} \frac{\Theta d_0^3(1-p) + \beta_i^2}{\Theta d_0^3 + \beta_i^2} d\beta_1 \cdots d\beta_{(k-1)} \\ &= \frac{1}{(k-1)!}\left[\beta_k - atan\left(\frac{\beta_k}{\sqrt{\Theta d_0^3}}\right) p \sqrt{\Theta d_0^3}\right]^{(k-1)} \end{aligned} \quad (17)$$

Therefore, putting Eq. (17) into Eq. (16) gives us

$$\begin{aligned} &P_s(SIR \geq \Theta) \\ &= \int_0^{\infty} \left[\left(\beta - atan\left(\frac{\beta}{\sqrt{\Theta d_0^3}}\right) p \sqrt{\Theta d_0^3}\right)^{(k-1)} \right. \\ &\left. \cdot \frac{(1-p)\Theta d_0^3 + \beta^2}{\Theta d_0^3 + \beta^2} e^{-\gamma\pi\beta_k} \frac{(\gamma\pi)^k}{(k-1)!}\right] d\beta \end{aligned} \quad (18)$$

4.2 RECMAC Algorithmic Complexity Analysis

Given the known limited computation, storage, and bandwidth resources in vehicular networks [22], complex algorithms may not be the best option to implement in vehicular networks, especially when maintaining optimal reliability of safety-related messages is one of the objective. Hence, one of our intrinsic goal in addition to guaranteeing transmission reliability with a sustained increasing rate in overall network throughput by applying random network coding performed over a Galois Field, $GF(k^n)$ is to design a vehicular communication scheme with a light-weight, low complexity algorithm that will be easily implemented in vehicular network environments. So, in this sub-section, we investigate the level of algorithmic complexity of RECMAC scheme. We concisely illustrate the feasibility of our proposed RECMAC algorithm and its applicability over VANETs by investigating the computational complexity involved with the encoding, re-encoding, and decoding processes.

Firstly, unlike conventional wireless networks, mobile vehicles in vehicular networks maintain a periodic status messages, which are broadcasted at regular intervals to inform neighbouring vehicles of their speed, direction of movement, and other kinematic information. These periodic messages, though, very small packets, can lead to an overwhelming network signalling complexity especially in saturated communication scenarios. In order to avoid this heavy network signalling complexity, so as to overcome its corresponding counter-effect, RECMAC scheme sub-divides the network into separate small manageable clusters to maintain a low signalling complexity and minimize network overhead. Therefore, there are a total of k broadcasted packets for $k|k \leq \mathbb{N}$ number of CMs in a given cluster, since the broadcasting is usually constrained within the source clusters. Apparently, it shows that the complexity of the network signalling can be regarded as linear $O(\mathbb{N})$, given that signalling overhead is constrained through manageable clusters.

Secondly, we consider the level of overhead complexity incurred as a result of the processes of packets encoding, re-encoding and decoding. In the process of packets coding, the source vehicle randomly generates an $\mathbb{M}$ encoding co-efficient, such that $\mathbb{M} \leq \mathbb{N}$, over the Galois field ($GF(q)$), which is used to generate a linear combination of P raw packet blocks. In the same way, the re-encoding processes also involves random generation of $p|p \leq \mathbb{N}$ coding co-efficients over the Galois field ($GF(q)$) in order to generate a linear combination of the initial coded messages $\mathbb{C}$ with any available P raw data packet blocks. Thus, it follows that the computational complexity associated with both raw packets encoding and the coded packets re-encoding processes could be considered as linear, (i.e., $O(\mathbb{N})$), and very low given that the total number of vehicles belonging to a particular cluster is usually small, especially in a highway scenario. In the same manner, given that each vehicle decodes the encoded data through Gaussian elimination technique, it follows that its complexity can be regarded as cubic $O(\mathbb{N}^3)$ and computationally lead to low complexity.

4.3 RECMAC Broadcast Reliability Analysis

In order to estimate message transmission reliability of vehicular networks using RECMAC scheme, we define a new reliability estimation metric called Packet Delivery Failure (PDF) ratio so as to evaluate the performance reliability of the proposed vehicular communication protocol. PDF ratio is defined as the ratio of the total number of packets that are not correctly received or recovered at the destination vehicles to the total number of packets transmitted from the transmitter.

Generally, in wireless communication, the total power consumptions are categorized into, 1) power consumptions due to power amplifier P_A, and 2) power consumptions due to other functioning circuits. As a result, when an energy is lost with a path loss exponent $\mathcal{L}$ determined empirically over AWGN due to fading channel, then, the received signal power P_r can be expressed as

$$P_r = h^2 P_{d_0} \left(\frac{d_0}{d}\right)^{\mathcal{L}}, \quad 2 \leq \mathcal{L} \leq 8 \qquad (19)$$

where h denotes the channel gain, $\mathcal{L}$ is the path loss exponent, d_0 represents the transmitter-receiver close-ranged reference distance, d denotes the packet transmission distance between the transmitter and the receiver, and P_{d_0} is the reference received signal power at the transmitter-receiver close-ranged reference distance, d_0. Hence, the overall reference received signal power P_{d_0} can be computed approximately as in [23]

$$P_{d_0} = \frac{G_r G_t f^2 P_A}{M_l N_f [(4\pi d_0)^2 (1+\alpha)]} = \frac{R_b E_b G_r G_t f^2}{M_l N_f [(4\pi d_0)^2 (1+\alpha)]} \qquad (20)$$

where G_r and G_t denote the receiver and transmitter antenna gain, respectively, f denotes the carrier frequency, N_f and M_l represent the receiver noise figure and link margin, respectively, R_b and E_b represent the basic transmission bit rate and the received energy due to amplifier per one bit of data that is transmitted, respectively, and $\alpha = (\zeta/\beta) - 1$ with ζ representing peak to average ratio that largely depends on the type of modulation scheme adopted and the corresponding size of constellation, while β denotes the drain efficiency of the radio frequency (RF) power amplifier. Since ζ largely depends on type of modulation scheme that is used and its corresponding size of constellation, adopting multiple quadrature amplitude modulation (MQAM) scheme makes $\zeta = 3\left[\left(\sqrt{M}-1\right)/\left(\sqrt{M}+1\right)\right]$. The received signal to noise ratio, SNR_r can be obtained by putting Eq. (20) into Eq. (19) as

$$SNR_r = \frac{P_r}{N_0 R_b} = h^2 \left(\frac{G_r G_t f^2 d_0^{\gamma-2}}{M_l N_f d^{\gamma} [(4\pi)^2 (1+\alpha)]}\right)\left(\frac{E_b}{N_0}\right) \qquad (21)$$

where N_0 denotes the single side thermal noise power spectral density. This is built on the assumption that the channel gain complies with the narrowband Rayleigh block fading distribution, so that its probability density function can be expressed as

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-\left(\frac{x^2}{2\sigma^2}\right)}, \quad for\ x \geq 0 \qquad (22)$$

with the cumulative distribution function (CDF) given as

$$F(x) = 1 - e^{-\left(\frac{x^2}{2\sigma^2}\right)}, \quad for\ x \in [0,\infty) \qquad (23)$$

where σ denote the scale parameter of the Rayleigh distribution. Therefore, the wireless vehicular communication link's packet loss probability, P_{loss} will be given by

$$P_{loss} = P_r(SNR_r \leq SNR_0) = P_r\left[h \leq \sqrt{\frac{cN_0 d^{\gamma}}{E_b}}\right]$$

$$= 1 - e^{-\left(\frac{cN_0 d^{\gamma}}{E_b}\right)} \quad (24)$$

where

$$c = \frac{SNR_0 M_l N_f\left[(4\pi)^2\left((1+\alpha)\right)\right]}{G_r G_t f^2 d_0^{\gamma-2}} \quad (25)$$

As discussed in the Section 3.4, suppose that there is j vehicles which are members of the cluster, then, each encoded packet broadcasted from the last hop is guaranteed to be successfully received by the participating stations in that cluster so far that it can be received by at least one of the j vehicles. Therefore, the probability of successfully receiving a broadcasted packet equal to $1-(P_{loss})^j$. Suppose that there is a total of k number of encoded messages amongst the N generated native and the received packets to be broadcasted from the last hop, then, the probability of successfully receiving both the j and k of N can be computed approximately as

$$P(j,k) = \left[\binom{N}{k}\left(1-(P_{loss})^{(j+k)}\right)\right]^{(N-k)} \quad (26)$$

Note that in introduction of the proposed protocol in Section 3.1, it is stated that the payload, C in each encoded message is the linear combination through bitwise exclusive OR (XOR operation) of the A original generated native and received packets. It follows that C can only be recovered if the rank of the encoding matrix that makes up the encoding vectors v which is attached with the received encoded messages is not greater than A. That is, $rank(v_r) \le A$, then, the original packets P_i (where $i = 1,2,\dots n$) can be recovered by Gaussian elimination. However, the coded packets decoding conditions may not always be satisfied by the k^{th} packets received by the destination vehicle, given that the encoding vectors v_r are randomly generated over $GF(k^n)$. Hence, a new defining parameter p_A is introduced, which denotes the probability that the rank of $\mathcal{B}$, which is an $m \times n$ coding matrix that is randomly generated over $GF(k^n)$ is equal to $min(m,n)$. Apparently, $p_A = 1$ when $rank(\mathcal{B}) \le min(m,n)$. In other words, the rank of $\mathcal{B}$ is a non-negative integer and cannot be greater than either m or n. That is to say that p_A expresses the probability that the decoding conditions are not satisfied by the m randomly generated $1 \times n$ encoding vectors. Consequently, over a $GF(k^n)$, the exact value of p_A can be obtained as in [24]:

$$p_A = \begin{cases} 1 - \prod_{q=0}^{m-1}\left(1 - \frac{1}{k^{n-q}}\right), & for\ rank(\mathcal{B}) \ge min(m,n) \\ 1, & for\ rank(\mathcal{B}) < min(m,n) \end{cases} \quad (27)$$

From Eq. (27), the chances of recovering original packets, A, decreases as the resulting values of the probability p_A get relatively very small for $rank(\mathcal{B}) > min(m,n)$. As a result, PDF in one hop broadcast (i.e., except the last hop broadcast) can be computed approximately as

$$PDF_0 = \sum_{j=0}^{N}\sum_{k=0}^{N}\binom{N}{j}\left[\left(1-(P_f)^{(j)}\right)(P_f)^{N-j}\right].\binom{N}{k}\left[\left(1 - (P_{loss})^{(j)}\right)^k (P_{loss})^{j(N-k)}\right].p_A \quad (28)$$

where P_f denotes the probability that a transmitted encoded packet is not successfully received. Thus, the PDF_l can be computed approximately for the encoded packet's last-hop transmission as

$$PDF_l = \sum_{j=0}^{N-1}\sum_{k=0}^{N}\binom{N-1}{j} \cdot \left[\left(1-(P_f)^{(j)}\right)(P_f)^{N-1-j}\right].\binom{N}{k}\left[\left(1 - (P_{loss})^{(j+1)}\right)^k (P_{loss})^{(j+1)(N-k)}\right].p_A \quad (29)$$

Finally, from Eq. (28) and (29), the total packet delivery failure ratio, PDF_t becomes

$$PDF_t = 1 - [(1-PDF_0)\cdot(1-PDF_l)] \quad (30)$$

5. Simulation Setup

In this section, a comparison of RECMAC and the reference protocol (CARER) [5] is shown using simulation experiments, focusing on a highway scenario with 300 vehicles.

5.1 Simulation Settings

In this section, a close to real-life vehicular network simulation scenario based on Nakagami model for the V2V communication link is presented. We used MatLab to implement the simulator based on the assumed system model and channel in Section 3. 300 smart vehicles are spaced horizontally along a two-lane highway of opposite direction with an intra-vehicle spacing of 30m in a 1km highway road segment. Each vehicle broadcasts with a 12 Mbps channel rate. The results of our simulation experiments are averaged over 500 runs.

Given that the erasure probability is a basic performance factor for evaluating the transmission reliability, a realistic V2V communication channel is considered, with the erasure probability given as a function of distance in a typical vehicular network environment. The probability density function of the signal amplitude X based on this assumed channel model is

$$fX(x) = \frac{2m^m x^{(2m-1)}}{m(P_r)^2} exp\left(-\frac{mx^2}{2P_r}\right)$$
$$m \ge \frac{1}{2}, P_r > 0$$

where m is the Nakagami-m channel fading figure, and P_r denotes the total received power. Molisch *et al.* [25] reported a path loss component (i.e., 1.8 – 1.9) for a typical free highway vehicular communication environment. In our simulation, we assumed a path loss component of 2 for highways. In [26], Chen *et al.* estimated the fading figure m

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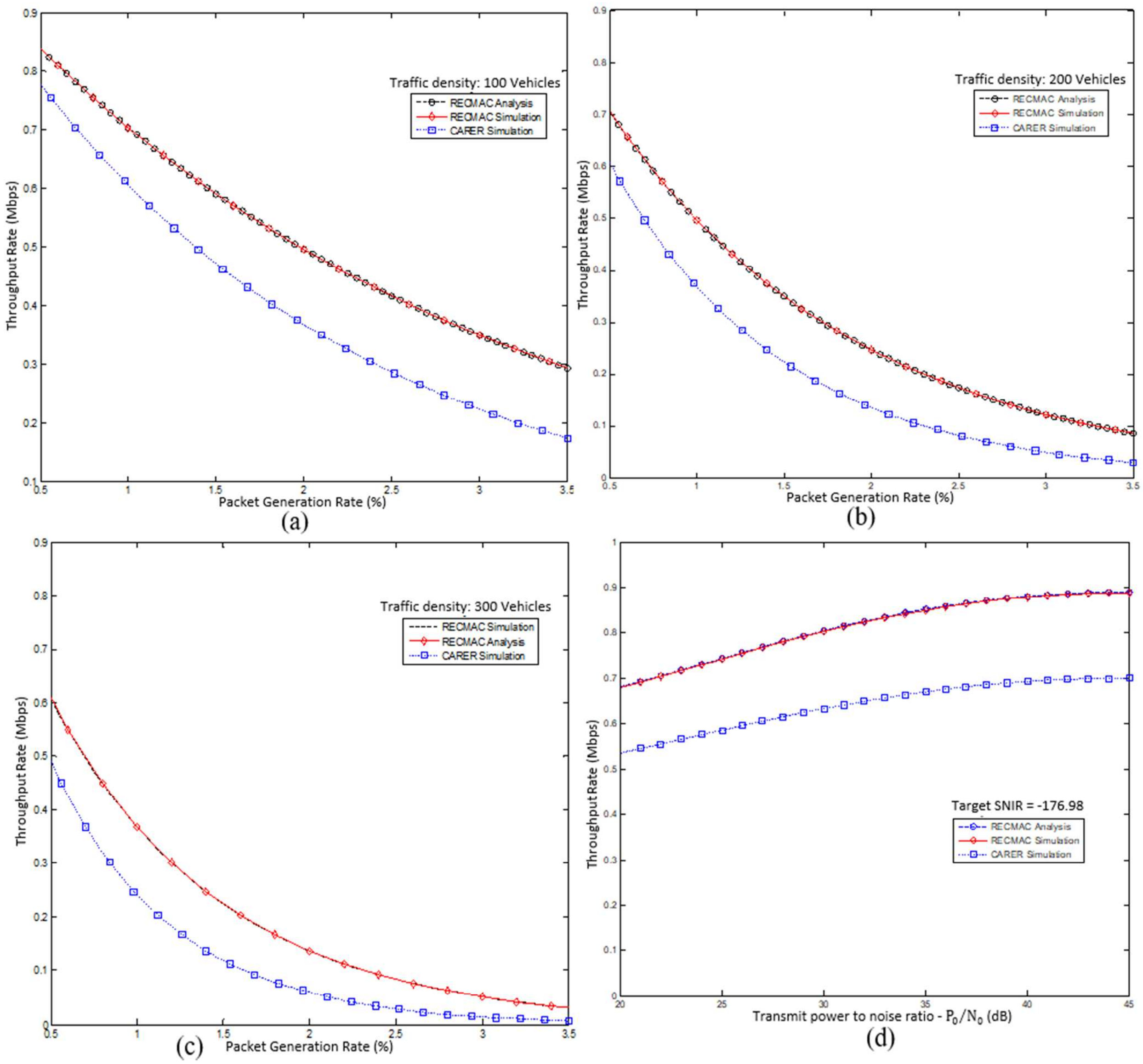
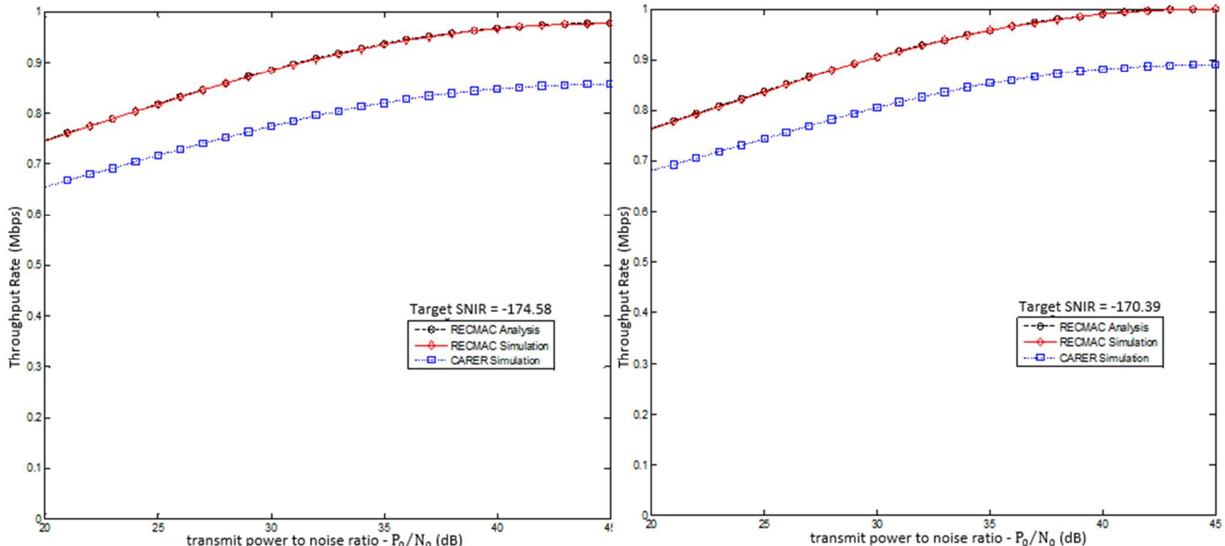
on empirical measurement for a free highway V2V communication link as

$$n = \begin{cases} 0.75, & d > 80 \\ 1.5, & d < 80 \end{cases}$$

To further estimate the performance of RECMAC scheme using a closer to real-life network model, we also performed further implementation of RECMAC in the Network Simulator II (ns-2) [27] with the realistic mobility pattern of the vehicles generated using Simulation of Urban





(e) (f)

Fig. 4. *Performance comparisons between the RECMAC and CARER scheme using (a) – (c) throughput rate (Mbps) as a function of percentage of packet generation rate with increasing vehicular traffic density from 100 to 300 vehicles, and (d) – (f) throughput rate (Mbps) as a function of transmit power to noise ratio -* P_0/N_0 *(dB) with increasing target SNIR* Θ *from -174.98 to -170.39.*

MObility (SUMO) [28]. All other parameters such as radio frequency, reception, and carrier threshold, etc, are also configured according to the specification of IEEE 802.11p/DSRC standard.

5.2 Results and Discussion

For the simulation, a Bernoulli random variable and an exponential random variable are generated to represent the packet transmission event of each mobile vehicle and Rayleigh fading channel, respectively. We also set some of the dimensionless network parameters such that the path loss attenuation factor $\alpha = 3$, transmission power $P_0 = 1$, and radius of the cluster $r = 2$. The coefficients of the random network coding are randomly generated over a $\mathbb{G}(2^8)$ Galois Field. The wireless channel between the broadcasting vehicle and the receiving vehicles is modelled by joint log-distance path loss model and Rayleigh fading.

In Fig. 4 (a) – (c), we report on the effects of packet generation rate on the overall network throughput performance, and we see that as the percentage of packet generation rate increases, as anticipated, the channel utilization decreases greatly. It is noteworthy to notice that as the percentage of packet generation rate rapidly increases, the resultant diminishing effect becomes more and more acute. This can be explained by the fact that the increased percentage of packet generation rate obviously resulted in increased contention for channel utilization both with intra-cluster by the participating CMs and inter-cluster by CHs in control of cluster to cluster message exchange. In other words, the resulting significant increase of collision probability adversely affects the performance, especially in terms of throughput deterioration.

The overall network throughput performance of both RECMAC and CARER schemes start to decrease significantly as the percentage of packet generation rapidly increases towards 3.5 (see Fig. 4 (a) – (c)). This rapid decrease in terms of network throughput across both protocols became worse from Fig. 4(a), 4(b) to 4(c) due to increased contention for channel access caused by high network saturation as the rate of packet generation increases under heavy network density (from traffic density of 100 vehicles to 300 vehicles). This observed rapid decrease in the overall network throughput performance for both schemes is caused by increased, heavy network overhead as a result of increased channel congestion and contention due to high percentage of packets generation rate across the entire network. In other words, the increased, heavy network overhead created by increased percentage of packets generation rate practically exhibits an over-bearing effect on the performance.

However, this effect of increased network overhead is more adverse on CARER scheme compared to RECMAC as can be seen in Fig. 4(a), 4(b) and 4(c). It is observed that RECMAC scheme offers a performance advantage of multiple orders of magnitude against CARER scheme in terms of network throughput. This can be partly due to: 1) the fact that the RECMAC minimizes the effect of contention for channel utilization by sub-dividing the entire network into separate manageable clusters with CHs that control both intra-cluster and inter-cluster communication (including our developed *refined CM-to-CH handshake*), which undeniably avoids heavy network overhead as a result of increased channel congestion and contention; and 2) the complex rebroadcasting node selection metric [5] used by CARER scheme to determine and select the most suitably qualified candidate (i.e. vehicle) for rebroadcasting the encoded packets to enable the vehicles outside the radio coverage of the source vehicle to receive and decode the encoded messages. Therefore, as opposed to RECMAC, which simply allows the CHs to re-encode and rebroadcast the coded messages to enable the clusters beyond the transmission coverage of the source vehicle to receive the encoded messages, CARER scheme incurs additional network overhead due to the high complexity of the rebroadcasting node selection metric and the processes involved in selecting a vehicle that will rebroadcast the encoded messages. In other words, this extra network overhead which the use of this selection metric incurs leads to the deterioration of CARER scheme network performance in terms of the achievable network throughput compared to RECMAC scheme.

In Fig. 4 (d) – (f), we show the effect of selecting an optimal target SNIR, Θ, on the performance, especially the network throughput. It can be clearly seen that the overall network throughput performance can be increased by selecting an optimal target SNIR, Θ, at the PHY layer as is evident in Fig. 4(d) through Fig. 4(f). It shows that with a high target SNIR, Θ , the encoded packets can be broadcasted with high spectral efficiency. However, the probability of successful transmission of the encoded and re-encoded packets, P_s, becomes very low. On the other hand, using a low target SNIR, Θ, many encoded and re-encoded packets that contain little information can be successfully transmitted. As can be seen from both the analytical and simulation results in Fig. 4(f), the optimal target SNIR, Θ, that maximizes the overall network throughput performance is -170.39 dB when transmit power to noise ratio $P_0/N_0 =$ 43 dB. It is noteworthy to mention that the selected optimal target SNIR, $\Theta = -170.39$ dB can be reduced if the noise level increases so as to minimize the channel error. Remarkably, the RECMAC scheme also demonstrated better performance compared to the CARER protocol as can be witnessed in Fig. 4(d) through Fig. 4(f). Similarly, this can be as a result of the fact that the RECMAC scheme minimizes excessive contention for channel utilization, which in turn, reduces the network overhead and its associated adverse effect of performance deterioration by using effective network segmentation through clustering approach. Hence, with the RECMAC protocol, the clustering concept helps to sub-divide the whole vehicular network into separate manageable sub-networks with low network overhead as opposed to CARER protocol, which incurs heavy network overhead with adverse effect over the performance due to the use of constant periodic status messages that are broadcasted at regular intervals in vehicular communication networks. The advantages of applying network clustering concept by RECMAC protocol includes primarily for boosting performance as well as improving network security. More so, the use of high complex algorithm oriented rebroadcasting node selection metric by the CARER protocol to search for a rebroadcasting node for the encoded messages as opposed to RECMAC scheme also leads to increased network overhead and spectral inefficiency, which at the long run, results to poor performance especially in terms of network throughput.

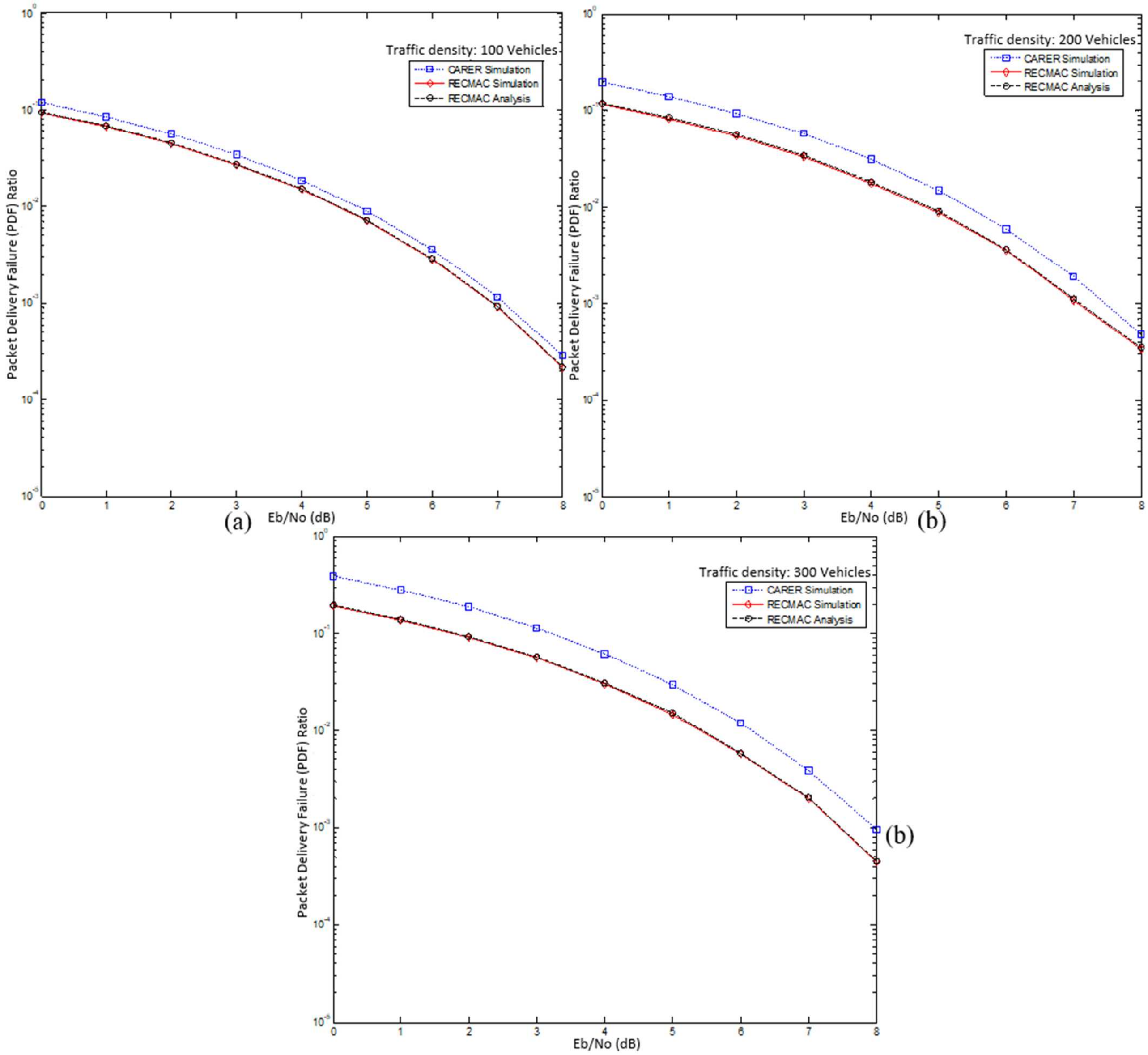


Fig. 5. *Performance comparisons between the RECMAC and CARER scheme using PDF_t ratio as a function of increasing rate of E_b/N_0 (dB) and vehicular traffic density from (a) 100 vehicles, (b) 200 vehicles to (c) 300 vehicles.*

The performance of the proposed RECMAC scheme against existing CARER protocol was also verified in terms of transmission reliability using the developed PDF_t ratio performance metric discussed in Section 3.3. The outcome of PDF_t ratio over varying transmit E_b/N_0 (dB) and vehicular traffic density changing from 100 vehicles to 300 vehicles with other parameters unchanged is measured in Fig. 5(a) through Fig. 5(c). As can be clearly seen in Fig. 5(a) through Fig. 5(c), RECMAC achieved better network performance in terms of transmission reliability than the CARER scheme with lower packet delivery failure ratio. Fig. 5(a) through Fig. 5(c) show that under the same condition of transmit E_b/N_0 (dB), the RECMAC scheme can offer a performance advantage of multiple orders of magnitude of lower PDF_t ratio than CARER protocol. As the rate of E_b/N_0 increases, the PDF_t ratio of both schemes drastically drops, accordingly, which means that the network transmission reliability performance is improved. Interestingly, across Fig. 5(a) – ((b), the PDF_t ratio of the proposed RECMAC did not only remain much lower than that of CARER scheme, but the performance gap between the two protocols widens as the traffic density increases from 100 vehicles in Fig. 5(a), and 200 vehicles in Fig. 5(b) to 300 vehicles in Fig. 5(c) with the largest PDF_t ratio performance gap. This can be explained by the fact that RECMAC applies node clustering concept, which was discussed above, as opposed to CARER as well as due to the use of high complex rebroadcasting node selection metric by the CARER protocol to search for the most suitably qualified vehicle that will rebroadcast the encoded messages to ensure wider coverage beyond the transmission range of the source vehicle.

However, Fig. 5(a) – (c) also show that both the RECMAC and CARER schemes exhibit gradual but steady increment in network performance deterioration in terms of transmission reliability as the traffic density increases as can be seen in Fig. 5(b) and Fig. 5(c) with 200 vehicles and 300 vehicles, respectively. This can be attributed to the fact that an increment in vehicular traffic density comes with an associated increase in percentage of packet generation rate with a corresponding increase in contention for channel utilization, which in turn, leads to increased overall network overhead. Unfortunately, heavy network overhead generally impacts the performance adversely.

6. Conclusion

In this study, we have proposed a novel RECMAC scheme that combines and leverages on the manifold potentials of RNC, vehicle clustering, and cooperative communication to improve transmission reliability, maximize total achievable throughput as well as optimize the performance. We designed an efficient vehicular cluster formation algorithm, which uses the Euclidean distance to segment the network into smaller manageable groups of vehicles (i.e. clusters) to achieve high reliability with very low overhead. The algorithm allows only vehicles moving in the same direction to group together so as to ensure stability in the life cycle of the vehicular clusters. We also designed a CH selection metric $\mathcal{F}(j)$, which is used to determine and select the most suitably qualified candidate to become the CH. Both the theoretical and simulation results demonstrate that the developed analytical model is accurate in calculating both the improved transmission reliability and the maximized achievable network throughput. The performance evaluation of RECMAC scheme in urban environments consisting of short road segments with intersections, will form an interesting future work to complement our proposed scheme so as to be applicable in both highway and urban vehicular communication environments.

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8. Appendices

1 Derivation of the Probability of Successful Transmission ($N_0 \neq 0$)

Let $\mathbb{Q}_0$ represent the total received power from the source vehicle, with $\mathbb{Q}_i$, such that $i = 1, 2, \cdots, k, i \neq (k/2)$ represents the received power as an exponential random variable with mean $\widetilde{\mathbb{Q}}_i$ from k potential interferers. It is noteworthy to mention that all the received powers are exponentially distributed, such that

$$p\mathbb{Q}_i(r_i) = \frac{1}{\widetilde{\mathbb{Q}}_i \cdot e^{(-r_i/\widetilde{\mathbb{Q}}_i)}}$$

where $\widetilde{\mathbb{Q}}_i = P_i d_i^{-\alpha}$ represents the mean received power. Consequently, the aggregate interference I (i.e., the sum average of the received power from each undesired transmitters) affecting the transmission at the recipient vehicle is given by

$$I = \sum_{i=1}^{k} \mathbb{Q}_i \cdot \mathbb{S}_i$$

where $\mathbb{S}_i$ denotes a sequence of independent and identically distributed (i.i.d.) Bernoulli random variables with $P(\mathbb{S}_i = 0) = (1 - p)$, and $P(\mathbb{S}_i = 1) = p$. Thus, both encoded and re-encoded messages are guaranteed successful delivery when both destinations have higher SNIR than the target threshold SNIR Θ. Therefore, the probability of successful transmission is expressed as

$$P_{st}(SNIR \geq \Theta) = E_I[P(\mathbb{Q}_0 \geq \Theta(N_0 + I) \mid I)^2]$$

$$= E_{\mathbb{Q},\mathbb{S}}\left[exp\left(-\frac{2\left[\Theta\left(\sum_{i=1, i\neq(k/2)}^{k} N_0 + \mathbb{Q}_i\,\mathbb{S}_i\right)\right]}{2\widetilde{\mathbb{Q}}_0}\right)\right]$$

$$= exp\left(-\frac{2N_0\Theta}{\widetilde{\mathbb{Q}}_0}\right) E_{\mathbb{Q},\mathbb{S}}\left[\prod_{i=1, i\neq(k/2)}^{k} exp\left(-\frac{2\Theta(\mathbb{Q}_i \mathbb{S}_i)}{\widetilde{\mathbb{Q}}_0}\right)\right]$$

$$= exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right) \cdot \prod_{i=1, i\neq(k/2)}^{k} \Bigg[P(\mathbb{S}_i = 1) \cdot \int_0^{\infty} exp\left(-\frac{2\Theta q_i}{\widetilde{\mathbb{Q}}_0}\right) . p2\mathbb{Q}_i(q_i) dq_i + P(\mathbb{S}_i = 0)\Bigg]$$

$$= exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right) \cdot \prod_{i=1, i\neq(k/2)}^{k} \frac{p}{1 + 2\Theta\left({}^{d_i}/_{d_0}\right)^{\alpha}} + (1 - p)$$

$$= exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right) \cdot \prod_{i=1, i\neq(k/2)}^{k} \left(1 - \frac{2\Theta p}{R^{\alpha} + 2\Theta}\right)$$

■

2 Derivation of the Probability of Successful Transmission ($N_0 = 0$)

The mean power from the i^{th} interferer with unit transmit power at distance $R_i | i = 1, 2, \cdots, k; i \neq (k/2)$ is $1/R_i^{\alpha}$. According to Mathar and Mattfeldt [20], the Laplace transform of an exponential distribution with mean $1/\lambda$ is $\lambda/(\lambda + l)$, $l \geq 0$. Hence, the Laplace transform of I as in [20] becomes

$$L_I(l) = \prod_{i=1, i\neq(k/2)}^{k} \left(\frac{pR_i^{\alpha}}{R_i^{\alpha} + l} + (1 - p)\right)$$

$$= \prod_{i=1, i\neq(k/2)}^{k} \left(1 - \frac{p}{\left(\frac{R_i^{\alpha}}{l}\right) + 1}\right)$$

From Eq.(10) and with $N_0 = 0$, $R_i = d_i/d_0$ (that is, normalized distances), the probability of successful transmission now becomes

$$P_{st}(SIR \geq \Theta) = \prod_{i=1, i\neq(k/2)}^{k} \left(1 - \frac{p}{\left(\frac{R_i^{\alpha}}{\Theta} + 1\right)}\right)$$

■