MAP: Contention-Free MAC protocol for VANETs with PLNC

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***Abstract*—We present MAP, a contention-free MAC protocol for fast and reliable multi-hop data dissemination in vehicular ad hoc networks which takes advantage of two-packet collisions to improve network capacity. MAP addresses both the problem of unwanted collisions due to hidden nodes in CSMA/CA-based networks, and the problem of excessive control messages in dense TDMA-based vehicular networks. MAP operation introduces: (i) a dynamic subdivision of the space into multiple sub-spaces using one relay node each, and (ii) a deterministic medium access that is free of control messages, while being favorable to physical-layer networking coding transmissions. MAP implements judicious broadcast phases to guarantee fast and reliable transmissions, while nodes can join or leave the dissemination process anytime. Numerical results show that with MAP, we can achieve fast and reliable all-to-all dissemination in large multi-hop VANETS compared to conventional techniques.**

I. Introduction

Vehicular ad hoc Networks (VANETs) are gaining considerable interest as they promise a host of innovative services for drivers and passengers. In VANETS, vehicles cooperate to deliver data through one or multiple hop paths, without the need of a centralized base station. VANETS made possible to have both new safety applications with advanced features to avoid or mitigate accidents, and innovative user applications which provide value-added services such as entertainment or data sharing. In this work, we are interested in data dissemination for user applications in all-to-all scenarios. That is, we consider vehicles to be involved in data sharing with all others around them. Use-cases are various, ranging from route discovery and routing protocols updates, to dissemination of alert messages in alert zones.

More explicitly, we address the following problem: N vehicles randomly distributed over a large vehicular network, want to share with each other some information (e.g. about their local traffic conditions) at an instant T_0 (e.g. so that they will end up with a global view of traffic conditions).

For VANETs, the adopted standard is DSRC (Dedicated Short Range Communications)/IEEE 802.11p [1] which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA is well known for its inefficiency in ensuring reliable data dissemination in dense communication networks. Thus, several techniques have been proposed to improve medium access in VANETS [2-8]. Some of these techniques use Time Division Multiple Access (TDMA) [4],[7], but either need to use control messages for transmissions coordination, or are intended for one-hop scenarios. Other works use Physical Layer Network Coding (PLNC) to improve data transmission efficiency. For example, the work in [9] uses PLNC to improve end-to-end transmission delay, but the use of control messages translates into some added communication overhead. In a previous work [10], we showed that with VPNC-MAC, a MAC protocol using PLNC, it is possible to achieve high reception rates in areas where all nodes can sense each others' transmissions. However, the scheme is not scalable to large multi-hop networks.

Our goal in this work is to provide fundamental elements of answer to the following question: How to schedule transmissions dynamically and efficiently so as to take advantage of simultaneous communications in multi-hop VANETs, while improving transmissions reliability, reducing dissemination completion time, and avoiding both unwanted collisions and the use of control messages?

To answer the above question, we propose a protocol called MAP (Medium Access for PLNC), which achieves fast and reliable all-to-all data dissemination among vehicles. MAP takes advantage of PLNC, which has been shown to improve wireless networks capacity, and avoid hidden node problems.

Our contribution in this work can be summarized as follows:

- We propose a channel access protocol in which nodes transmit simultaneously to create collisions of at most two packets at well-determined receiver nodes. The receiver nodes can fully decode the content of two interfering message signals, and can serve as relay nodes.
- We propose a contention-free medium access which avoids the hidden node problem, and does not require the exchange of control messages.
- We propose a fast, reliable, and scalable dissemination technique for VANETs, that makes use of network coding techniques and the notion of "zones", which are dissemination areas determined dynamically.

We organize the remainder of the paper as follows: in Section II, we present the system model, the assumptions, and the notations used throughout the paper. We describe MAP in Section III, and MAP priority-based indexation policy in Section IV. In Section V, we describe the dissemination technique used. A theoretical analysis is presented in Section VI, and numerical results are illustrated in Section VII. We finally conclude the paper in Section VIII.

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II. System model, assumptions and notations

We consider a 1-D network of length $L > 2r + 1$, where r is the transmission range of a vehicle. We assume that each vehicle is equipped with the global positioning system (GPS), and that a vehicle position is determined with a negligible error. We further assume that all the vehicles are synchronized to the Coordinated Universal Time (UTC). The sensing range of a vehicle corresponds to its communication range, and we assume this range to be the same for all vehicles. A receiver in the communication range of the transmitter decodes without error the packet transmitted. When a collision of two packets is received, the receiver can detect it and correctly decode the content of each individual packet [11]. Collisions of more than two packets are not decoded. We also assume that the network is divided into multiple adjacent zones, and two adjacent zones contain at least one node in common to serve as inter-zone relay. The determination of zones and relay nodes is described in Section III. Fig.1 illustrates the zones. In the following, we use the terms service and dissemination service interchangeably, and vehicle or node refer to any vehicle interested in the service, unless specified otherwise.

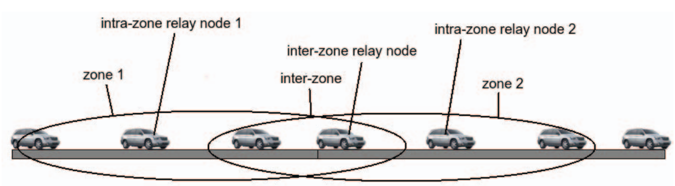

Fig. 1: Zone, intra-zone relay node, and inter-zone relay node.

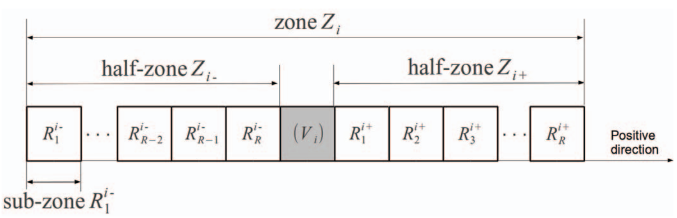

Fig. 2: A zone with its half-zones and sub-zones.

III. Description of MAP

MAP is a deterministic scheme based on the location of vehicles within the network. In MAP, the network is divided into sub-zones of equal length λ. The length λ of the sub-zone basically corresponds to the average distance that separates two consecutive vehicles interested in the service. The value of λ depends on the application using the dissemination service and its choice can take into account criteria such as the traffic density, etc. Its impact on the performance of MAP will be discussed later in the paper. This can guide the choice of its value depending on the application.

MAP protocol works as follows: At the initiation of the service, nodes compete using standard CSMA/CA to access the channel. A node that succeeds, transmits during this phase information containing its position, and the λ parameter. This node will be called intra-zone relay node.

Definition 1. *(relay node or intra-zone relay node) An intra-zone relay node is the node that initiates the service in a zone.*

Definition 2. *(zone) A zone is any region of the network delimited by the communication range of the relay node. It consists in a finite number of consecutive intervals of length λ referred to as sub-zones.*

Based on the information received from the intra-zone relay node, each vehicle within its range determines its relative location in order to determine its sub-zone index. The index serves as the default transmission sequence order of the vehicle within it.

Definition 3. *(sequence) A transmission sequence refers to a two-step transmission mechanism as in PLNC. First, a multiple access phase in which two nodes transmit their packets to the relay node which fully decodes the interference packet [11], and second, a broadcast phase in which the relay node forwards a network-coded packet of the interfering packets.*

This way of assigning transmission sequences has several advantages. It is simple, completely decentralized, does not need control messages and allows to easily coordinate transmissions between partially superposed adjacent zones.

Definition 4. *(inter-zone) The inter-zone is the set of sub-zones belonging both to the positive half-zone and the negative half-zone of two adjacent zones.*

Definition 5. *(positive/negative half-zone) The positive half-zone is the set of sub-zones located in front of the relay node with respect to its direction of movement, while the negative half-zone is the set of sub-zones located in its back.*

In general, the superposition of zones represents a source of challenging issues for communication protocols, including hidden node problems. MAP addresses this aspect with a priority-based indexation scheme. When *priority-k* is used, it means that the node has to sense the channel idle for kT_{SIFS} before transmitting; T_{SIFS} being the minimum time required to detect an ongoing transmission. When an inter-zone node does not transmit because of detected ongoing transmissions, it postpones its transmission to the next *MAP session*.

Let us consider a single relay node (V_i) of a zone as shown in Fig. 2. Let R be the highest sub-zone index, then: $\mathcal{R}_j^{i+}$ (resp. $\mathcal{R}_j^{i-}$) represents the *sub-zone* located at distance $j\lambda \pm \lambda/2$ (resp. $(R - j + 1)\lambda \pm \lambda/2$) from the relay node ($V_i$), and $\mathcal{Z}_{i+}$ (resp. $\mathcal{Z}_{i-}$) represents the positive (resp. negative) half-zone of the zone $\mathcal{Z}_i$. And, when the need of specifying the priority-k of a node is required, we write $\mathcal{R}_{j[k]}^{i+}$ instead.

Definition 6. *(session) A MAP session or simply a session is the period of time $\Delta_{sess} = R\Delta_{seq}$ required to complete R transmission sequences of duration Δ_{seq} each.*

The number of sub-zones within the inter-zone may vary from one to R, and has an impact on the the dissemination

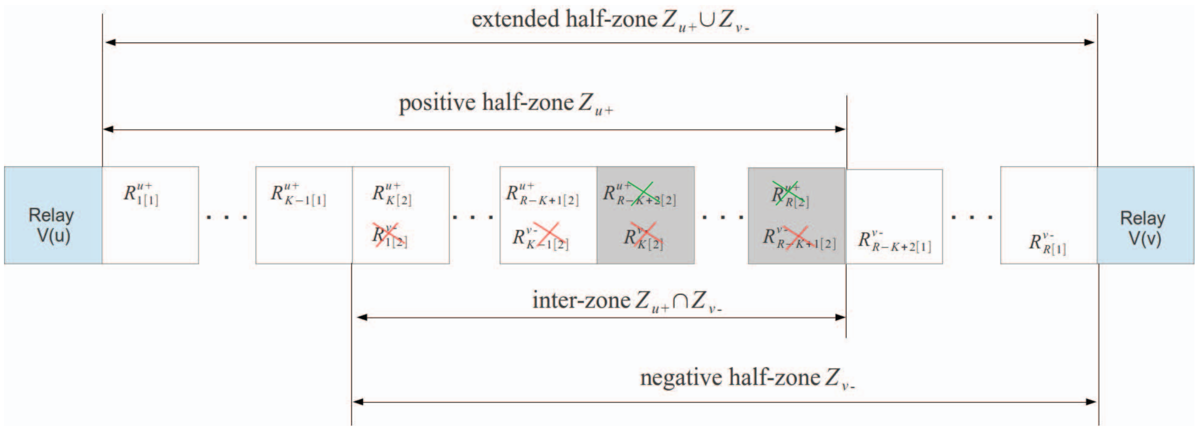

Fig. 3: Transmission sequence indexation and priority assignment when the session order $\mathcal{O}_{\text{sess}}(t)$ is odd and $K < \frac{R}{2} + 1$.

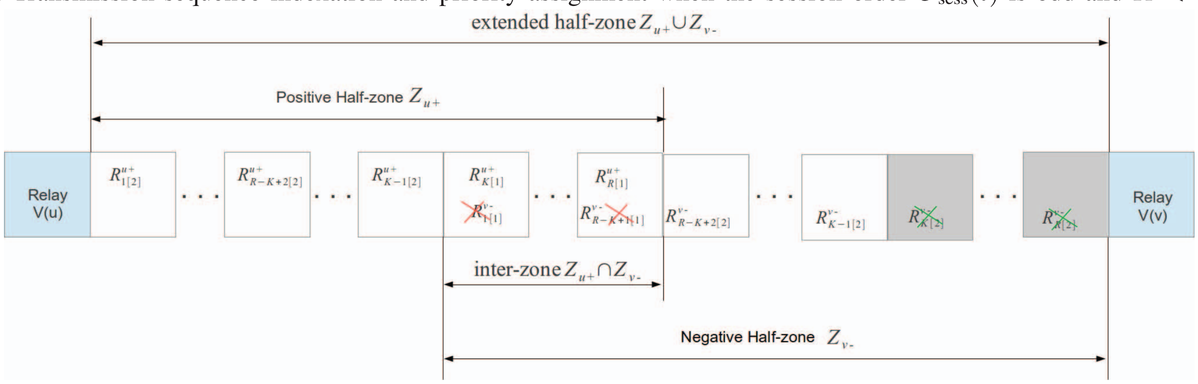

Fig. 4: Transmission sequence indexation and priority assignment when the session order $\mathcal{O}_{\text{sess}}(t)$ is even and $K \geq \frac{R}{2} + 1$.

process performance. When this number is less than $R/2$ (see Fig. 3 and Fig. 4), it is important to notice the presence of *exposed-sequence* nodes within the *extended half-zone*.

Definition 7. *(extended half-zone) The extended half-zone designates the set of sub-zones of both the negative half-zone and the positive half-zone of two adjacent zones.*

Definition 8. *(exposed-sequence nodes) The exposed-sequence nodes are the non inter-zone nodes of the extended half-zone that have the same sequence index.*

Exposed-sequence nodes do not belong to the same half-zone and can therefore be in the same extended half-zone while transmitting to different intra-zone relay nodes.

MAP targets to achieve all-to-all dissemination throughout the extended half-zones first. Extending the dissemination to multiple adjacent extended half-zones is straightforward.

IV. Indexation and Prioritization in MAP

A. Step 1: indexation initialization

The determination of the index of a sub-zone is relatively simple. Basically, a vehicle located at the relative distance (to the intra-zone relay node) $d = j\lambda \pm \lambda/2$ in the positive half-zone is in the sub-zone j, while the vehicle located at the same distance in the negative half-zone is in the sub-zone $R-j+1$, where R is the highest possible index.

B. Step 2: indexation of inter-zone nodes

When two zones interfere, the positive half-zone and the negative half-zone of the respective zones have sub-zones with conflicting indexations. To deal with this indexation issue, sub-zones within the inter-zone keep the indexation given by the positive half-zone.

C. Step 3: prioritization of inter-zone nodes

The "change" of index in interfering negative half-zones leads to the presence of repeated sequences. That is, several pairs of sub-zones will have the same sequence. These sequences that appear twice in the negative half-zone are referred to as *conflictual-sequences* throughout the paper. To overcome this issue, because no more than one node within a half-zone can transmit during the same sequence (decoding of collisions is limited to two colliding packets), MAP incorporates a prioritization mechanism in the indexation: nodes within the inter-zone have a lower priority compared to the *non inter-zone nodes*. We say that non inter-zone nodes are of *priority-1*, and inter-zone nodes are of *priority-2*.

D. Step 4: prioritization due to inactive sub-zones

Given that it might be difficult for the application to determine an optimal value of λ, it is possible to have empty sub-zones, and hence no transmission during some sequences (meaning a waste of bandwidth). MAP implements additional service differentiations to overcome such an issue. The number of additional priorities is based on the fact that the maximum possible error in determining λ at the application layer is $\pm\lambda$. This means that, given λ, the service is sure to find at least one vehicle interested in the dissemination within two consecutive sub-zones of length λ each. Hence, to avoid empty multiple access phases, the non inter-zone node of sub-zone index j can transmit at sequence $j-1$ with priority-3 if no ongoing transmission is detected.

E. Session order and prioritization

To prevent large dissemination delays, MAP further implements a *session order* prioritization scheme.

Definition 9. *(session order) The session order represents the number of sessions since the service initiation.*

The session order is denoted by $\mathcal{O}_{\text{sess}}$ and is determined at any UTC instant t as follows:

$$\mathcal{O}_{\text{sess}}(t) = \lceil \frac{t}{\Delta_{\text{sess}}} \rceil. \tag{1}$$

In fact, when the session order is odd, as in service initiation ($\mathcal{O}_{\text{sess}=1}$), sub-zones indexation and prioritization are performed as described above. When the session order is even, a few changes that can benefit the dissemination process are required. Indeed, the indexation in the first session basically results into high indexes, and thus large network allocation vectors (NAV). To equilibrate this, the inter-zone nodes adopt the indexation given by the negative half-zone when the session order is even. In other words, when the session order is even, the priority order between non inter-zone nodes and inter-zone nodes is reversed.

Fig. 3, and Fig. 4 summarize the indexation and prioritization for different parities of session order. In these figures, red crosses indicate sub-zones with transmission sequence indexes canceled, green crosses indicate sub-zones where conflictual-sequences with priority-2 will be postponed in case of conflict with priority-1 sequences, and gray sub-zones indicate sub-zones that may need to transmit during the next session.

V. Dissemination mechanism

MAP implements two types of disseminations to achieve reliability and fast all-to-all data distribution over the network.

A. Intra-zone dissemination

Dissemination inside a zone is ensured by means of broadcast phases. In MAP, each multiple access phase is followed by a broadcast phase during which the intra-zone relay node forwards the received packets to other nodes in the same zone.

B. Inter-zone dissemination

Inter-zone dissemination ensures that each non inter-zone node of the positive (resp. negative) half-zone possesses the packets of the non inter-zone nodes of the negative (resp. positive) half-zone of the same extended half-zone. Hence, we define in MAP a second type of relay node: the *inter-zone relay node* which forwards packets of non inter-zone nodes.

Definition 10. *(inter-zone relay node or inter-zone relay) The inter-zone relay node is the inter-zone node located at the farthest active sub-zone within the positive half-zone.*

The inter-zone relay has the lowest priority order in a sequence ($k_{\max} = 5$); that is, at any sequence $j = 1, ..., R$, the inter-zone relay has priority-5 to forward the packets using PLNC. The inter-zone relay possesses two queues: the Q_u queue for packets of type-u, that is packets from nodes of the $\mathcal{Z}_{u+}$ half-zone, and the Q_v queue for packets of type-v, that is packets from nodes of the $\mathcal{Z}_{v-}$ half-zone. The queues work on the principle of First In First Out (FIFO); if the inter-zone relay node can transmit and none of its queues is empty, the packet forwarded is a network-coded packet of the packets of type-u and type-v. The rate at which each queue is filled/emptied depends on the location and the sequences of the sub-zones from which the packets are emitted. To distinguish inter-zone relay transmission sequences from other transmission sequences, we refer to the former as *broadcast-sequences*, and to the latter as *information-sequences*.

VI. Theoretical analysis of MAP

A. Priority-based access time

Per MAP, a non inter-zone node whose sub-zone index is j transmits packets with priority-1 for odd session orders (resp. priority-2 for even session orders), and the transmission takes place when its priority-1 timer expires (resp. priority-2 timer for an even session order) . This timer corresponds to the corresponding NAV which is updated at the end of each transmission sequence (every time the node receives a packet from the relay node). NAV$[j, k, T]$ specifies the access time relatively to T at which the vehicle in the jth sub-zone with *priority-k* is allowed to attempt (start: the transmissions are deterministic) transmission. It is given by

$$\text{NAV}[j, k, T] = (j - v(T) - 1)\Delta_{seq} + kT_{\text{SIFS}}, \tag{2}$$

where, $v = v(T)$, the rank of the ending transmission sequence, is given by

$$v = \frac{T - (\mathcal{O}_{sess}(T) - 1)\Delta_{sess}}{\Delta_{sess}} + kT_{\text{SIFS}}. \tag{3}$$

To preserve transmission sequences synchronization, Δ_{seq} is fixed and corresponds to

$$\Delta_{seq} = \Delta_{mac} + \Delta_{bro}, \tag{4}$$

where Δ_{mac} and Δ_{bro}, respectively the duration of multiple access (mac) phase and the duration of broadcast (bro) phase of the sequence are given by

$$\Delta_{mac} = k_{\max}T_{\text{SIFS}} + T_{\text{data}}, \tag{5}$$

$$\Delta_{bro} = T_{\text{SIFS}} + T_{\text{data}}, \tag{6}$$

with $k_{\max}$ being the lowest priority order allowed in MAP, and $T_{\text{data}} = \alpha T_{\text{SIFS}}, \alpha >> k_{\max}$ being the length (transmission duration) of the packet transmitted. Note that once a node no longer has packets to transmit, it stays quiet until it gets a new packet to transmit. Also, an inter-zone node of the sub-zone whose index is j has two priorities: it uses priority-2 to transmit at the jth sequence for an odd session order (resp. priority-1 for an even session order), and it uses priority-4 to transmit at the $j-1$th sequence for an odd session order (resp. priority-3 for an even session order) .

B. Dissemination completion time

In this section, we determine the time at which the dissemination of each packet to all the nodes in the 1-D network is completed. For simplicity of presentation, we consider two cases: the case of a single half-zone, and the case of an extended half-zone. The extension to a network of several consecutive extended half-zones is straightforward. We assume that each vehicle possesses only one packet to share with the others at the beginning of the dissemination process.

1) Single half-zone $\mathcal{Z}_{i+}$: Let us consider the single half-zone $\mathcal{Z}_{i+}$ with its following analytical representation:

$$\mathcal{Z}_{i+} = \left\{\mathcal{R}_1^{i+}, \mathcal{R}_2^{i+}, ..., \mathcal{R}_R^{i+}\right\}. \tag{7}$$

According to MAP, a *sequence* of transmission is judiciously assigned to each sub-zone of the zone. Let us denote by s the function which attributes a sequence of transmission to a sub-zone. Throughout the paper, this function will be referred to as *sequence attribution function*. It is worth noting that the sequence is attributed to a sub-zone and not specifically to a node. This has the advantage to considerably reduce the complexity of the protocol. For any active sub-zone $\mathcal{R}_j^{i+}, 1 \le j \le R$, we have:

$$s(\mathcal{R}_j^{i+}) = \begin{cases} j-1, & \text{if no transmission is detected} \\ j, & \text{otherwise.} \end{cases} \tag{8}$$

Therefore, applied to a set $\mathcal{Z}_{i+}$, we obtain $\mathcal{S}_{i+}$ the set of sequences of $\mathcal{Z}_{i+}$:

$$\begin{aligned} \mathcal{S}_{i+} &= \cup_{\substack{1\le j \le R \\ \mathcal{R}_j^{i+} \neq \emptyset}} \left\{ s(\mathcal{R}_j^{i+}) \right\} & (9) \\ &= \left\{ S_1^{i+}, S_2^{i+}, ..., S_f^{i+} \right\}, & (10) \end{aligned}$$

where $f = \text{card}(\mathcal{S}_{i+})$, and $1 \le S_1^{i+} < S_2^{i+} < ... < S_f^{i+} \le R$.

Now, let us determine explicitly the dissemination completion time. The time Δ_{i+} after which the dissemination is completed corresponds to the time after which the last information-sequence ends. That is,

$$\Delta_{i+} = S_f^{i+} \Delta_{seq}, \tag{11}$$

where, Δ_{seq} is the duration of a sequence.

2) Extended half-zone $\mathcal{Z}_{u+} \cup \mathcal{Z}_{v-}$: Let us consider the *extended half-zone* $\mathcal{Z}_{u+\cup v-} = \mathcal{Z}_{u+} \cup \mathcal{Z}_{v-}$ resulting of the superposition of half-zones $\mathcal{Z}_{u+}$ and $\mathcal{Z}_{v-}$ of two relay nodes (V_u) and (V_v) in the same 1-D network such that the distance $d(V_u, V_v)$ between the two vehicles is $r < d(V_u, V_v) \le 2r$; r being the communication range of each vehicle. Let $q = \text{card}(\mathcal{Z}_{u+} \cap \mathcal{Z}_{v-})$ denote the number of sub-zones in the inter-zone $\mathcal{Z}_{u+} \cap \mathcal{Z}_{v-}$. We have:

$$\mathcal{Z}_{u+} \cap \mathcal{Z}_{v-} = \left\{ \mathcal{R}_{R-q+1}^{u+}, ..., \mathcal{R}_R^{u+} \right\} \tag{12}$$

with respect to $\mathcal{Z}_{u+}$ sequence ordering, or

$$\mathcal{Z}_{u+} \cap \mathcal{Z}_{v-} = \left\{ \mathcal{R}_1^{v-}, ..., \mathcal{R}_q^{v-} \right\} \tag{13}$$

with respect to $\mathcal{Z}_{v-}$ sequence ordering. But, given that a sub-zone belonging to an inter-zone adopts the sequence order of the positive half-zone (i.e., $\mathcal{Z}_{u+}$), the analytical representation of the inter-zone that holds is (12). Therefore,

$$\begin{aligned} \mathcal{Z}_{u+} \cup \mathcal{Z}_{v-} &= \left\{ \mathcal{R}_1^{u+}, ..., \mathcal{R}_{R-q}^{u+} \right\} \cup \left\{ \mathcal{R}_{R-q+1}^{u+}, ..., \mathcal{R}_R^{u+} \right\} \\ &\cup \left\{ \mathcal{R}_{q+1}^{v-}, ..., \mathcal{R}_R^{v-} \right\}. & (14) \end{aligned}$$

Depending on the value of q, two cases are considered:
Case 1: $q > R/2$. In this case, (14) becomes

$$\mathcal{Z}_{u+} \cup \mathcal{Z}_{v-} = \mathcal{Z}_{u+}^{1*} \cup \mathcal{Z}_{u+\cap v-}^{1*} \cup \mathcal{Z}_{u+\cap v-}^{1**} \cup \mathcal{Z}_{v-}^{1*}, \tag{15}$$

where,

$$\begin{cases} \mathcal{Z}_{u+}^{1*} = \left\{ \mathcal{R}_1^{u+}, ..., \mathcal{R}_{R-q}^{u+} \right\}, \\ \mathcal{Z}_{u+\cap v-}^{1*} = \left\{ \mathcal{R}_{R-q+1}^{u+}, ..., \mathcal{R}_q^{u+} \right\}, \\ \mathcal{Z}_{u+\cap v-}^{1**} = \left\{ \mathcal{R}_{q+1}^{u+}, ..., \mathcal{R}_R^{u+} \right\}, \\ \mathcal{Z}_{v-}^{1*} = \left\{ \mathcal{R}_{q+1}^{v-}, ..., \mathcal{R}_R^{v-} \right\}. \end{cases}$$

When we apply the sequence attribution function s to each sub-set of $\mathcal{Z}_{u+} \cup \mathcal{Z}_{v-}$, we have:

$$\begin{cases} \mathcal{S}_{u+}^{1*} = s(\mathcal{Z}_{u+}^{1*}) = \left\{ S_1^{1*u+}, ..., S_{a_1}^{1*u+} \right\}, \\ \mathcal{S}_{u+\cap v-}^{1*} = s(\mathcal{Z}_{u+\cap v-}^{1*}) = \left\{ S_1^{1*u+\cap v-}, ..., S_{a_2}^{1*u+\cap v-} \right\}, \\ \mathcal{S}_{u+\cap v-}^{1**} = s(\mathcal{Z}_{u+\cap v-}^{1**}) = \left\{ S_1^{1**u+\cap v-}, ..., S_{a_3}^{1**u+\cap v-} \right\}, \\ \mathcal{S}_{v-}^{1*} = s(\mathcal{Z}_{v-}^{1*}) = \left\{ S_1^{1*v-}, ..., S_{a_4}^{1*v-} \right\}, \end{cases} \tag{16}$$

where, $a_1 = \text{card}(\mathcal{S}_{u+}^{1*})$, $a_2 = \text{card}(\mathcal{S}_{u+\cap v-}^{1*})$, $a_3 = \text{card}(\mathcal{S}_{u+\cap v-}^{1**})$, $a_4 = \text{card}(\mathcal{S}_{v-}^{1*})$, and $1 \le S_1^{1*u+} < ... < S_{a_1}^{1*u+} < S_1^{1*u+\cap v-} < ... < S_{a_2}^{1*u+\cap v-} < \min\{S_1^{1*v-}, S_1^{1**u+\cap v-}\} < ... < \max\{S_{a_4}^{1*v-}, S_{a_3}^{1**u+\cap v-}\} \le R$, when $q > R/2$.

Case 2: $q \le R/2$. When $q \le R/2$, (14) becomes

$$\mathcal{Z}_{u+} \cup \mathcal{Z}_{v-} = \mathcal{Z}_{u+}^{2*} \cup \mathcal{Z}_{u+}^{2**} \cup \mathcal{Z}_{u+\cap v-}^{2*} \cup \mathcal{Z}_{v-}^{2*} \cup \mathcal{Z}_{v-}^{2**}, \tag{17}$$

where,

$$\begin{cases} \mathcal{Z}_{u+}^{2*} = \left\{ \mathcal{R}_1^{u+}, ..., \mathcal{R}_q^{u+} \right\}, \\ \mathcal{Z}_{u+}^{2**} = \left\{ \mathcal{R}_{q+1}^{u+}, ..., \mathcal{R}_{R-q}^{u+} \right\}, \\ \mathcal{Z}_{u+\cap v-}^{2*} = \left\{ \mathcal{R}_{R-q+1}^{u+}, ..., \mathcal{R}_R^{u+} \right\}, \\ \mathcal{Z}_{v-}^{2*} = \left\{ \mathcal{R}_{q+1}^{v-}, ..., \mathcal{R}_{R-q}^{v-} \right\}, \\ \mathcal{Z}_{v-}^{2**} = \left\{ \mathcal{R}_{R-q+1}^{v-}, ..., \mathcal{R}_R^{v-} \right\} \end{cases}$$

When we apply the sequence attribution function s to each sub-set of $\mathcal{Z}_{u+} \cup \mathcal{Z}_{v-}$, we have:

$$\begin{cases} \mathcal{S}^{2*}_{u+} = s(\mathcal{Z}^{2*}_{u+}) = \left\{S^{2*u+}_1, ..., S^{2*u+}_{b_1}\right\}, \\ \mathcal{S}^{2**}_{u+} = s(\mathcal{Z}^{2**}_{u+}) = \left\{S^{2**u+}_1, ..., S^{2**u+}_{b_2}\right\}, \\ \mathcal{S}^{2*}_{u+\cap v-} = s(\mathcal{Z}^{2*}_{u+\cap v-}) = \left\{S^{2*u+\cap v-}_1, ..., S^{2*u+\cap v-}_{b_3}\right\}, \\ \mathcal{S}^{2*}_{v-} = s(\mathcal{Z}^{2*}_{v-}) = \left\{S^{2*v-}_1, ..., S^{2*v-}_{b_4}\right\}, \\ \mathcal{S}^{2**}_{v-} = s(\mathcal{Z}^{2**}_{v-}) = \left\{S^{2**v-}_1, ..., S^{2**v-}_{b_5}\right\} \end{cases} \quad (18)$$

where, $b_1 = \text{card}(\mathcal{S}^{2*}_{u+})$, $b_2 = \text{card}(\mathcal{S}^{2**}_{u+})$, $b_3 = \text{card}(\mathcal{S}^{2*}_{u+\cap v-})$, $b_4 = \text{card}(\mathcal{S}^{2*}_{v-})$, $b_5 = \text{card}(\mathcal{S}^{2**}_{v-})$, and $1 \leq S^{2*u+}_1 < ... < S^{2*u+}_{b_1} < \min\{S^{2**u+}_1, S^{2*v-}_1\} < ... < \max\{S^{2**u+}_{b_2}, S^{2*v-}_{b_4}\} < \min\{S^{2*u+\cap v-}_1, S^{2**v-}_1\} < ... < \max\{S^{2*u+\cap v-}_{b_3}, S^{2**v-}_{b_5}\} \leq R$.

To determine the time of dissemination completion, we first need to find the time at which the last information-sequence takes place. According to MAP, only nodes within the inter-zone that are not able to transmit their packet during the first session are allowed to do so in the next session. They are nodes of $\mathcal{Z}^{1**}_{u+\cap v-}$ whose sequence coincides with those in $\mathcal{S}^{1*}_{v-}$. The set of these conflictual-sequences is then $\mathcal{S}^{1**}_{u+\cap v-} \cap \mathcal{S}^{1*}_{v-}$. Let $S^{\mathcal{S}^{1**}_{u+\cap v-} \cap \mathcal{S}^{1*}_{v-}}_{\text{min}}$ be the minimum conflictual-sequence during the first session. Then, according to MAP, the latest information-sequence will take place at sequence $R - S^{\mathcal{S}^{1**}_{u+\cap v-} \cap \mathcal{S}^{1*}_{v-}}_{\text{min}}$ of the second session.

However, in the case of an extended half-zone, additional relaying transmissions known as broadcast-sequences are necessary to achieve the all-to-all dissemination. Therefore, to determine the dissemination completion time, we finally need to find the number of broadcast-sequences required. Let $\mathcal{S}_x = \left\{S^x_1, S^x_2, ..., S^x_{n_x}\right\}$ denote the set of all the n_x information-sequences involving packets of type-x ($x = u, v$) excluding packets emitted from the inter-zone, and let $\mathcal{S} = \left\{S_1, S_2, ..., S_n\right\}$ be the set of all the n information-sequences during the first session. Let $f^{\mathcal{S}_x}_x$ denote the function that gives the number of packets of type-x present in the queue Q_x at the end of the last information-sequence of $\mathcal{S}_x$. We have

$$\begin{aligned} f^{\mathcal{S}_x}_x(S^x_{n_x}) &= -\min\left\{m_{n_x} - \hat{m}_{n_x}, f^{\mathcal{S}_x}_x(S^x_{n_x-1})\right\} \\ &+ f^{\mathcal{S}_x}_x(S^x_{n_x-1}) + 1, \end{aligned} \quad (19)$$

where, $m_{n_x} = \text{card}(\mathcal{S}_{x(n_x-1,n_x)})$, with $\mathcal{S}_{x(n_x-1,n_x)} = \left\{S^x_{n_x-1} + 1, S^x_{n_x-1} + 2, ..., S^x_{n_x} - 1\right\}$, and $\hat{m}_{n_x} = \text{card}(\mathcal{S}_{u(n_u-1,n_u)} \cap \mathcal{S}_v \cap \mathcal{S}_{u\cap v})$ if $x = u$, and $\hat{m}_{n_x} = \text{card}(\mathcal{S}_{v(n_u-1,n_u)} \cap \mathcal{S}_u \cap \mathcal{S}_{u\cap v})$ if $x = v$.

The number of packets present in the queue Q_x at the end of the last information-sequence of $\mathcal{S}$ is

$$f^{\mathcal{S}}_x(S_n) = \max\left\{0, f^{\mathcal{S}_x}_x(S^x_{n_x}) - (S_n - S^x_{n_x} - \text{card}(\mathcal{S}_{(n_x,n)}))\right\},$$

with $\mathcal{S}_{(n_x,n)} = \left\{S^x_{n_x} + 1, S^x_{n_x} + 2, ..., S_n\right\}$. For clarity, the main notations used are summarized in Table I.

TABLE I: Definition of symbols used for theoretical analysis.

Parameter	**definition**
L	Network length
r	Transmission range of the vehicle
λ	Average distance between two consecutive vehicles
R	Highest sub-zone index
$\mathcal{R}^{i+}_j$	*Sub-zone* located at distance $j\lambda \pm \lambda/2$ from relay node (V_i)
$\mathcal{R}^{i-}_j$	*Sub-zone* located at distance $(R - j + 1)\lambda \pm \lambda/2$ from relay node (V_i)
$\mathcal{Z}_{i+}$	Positive half-zone of zone $\mathcal{Z}_i$
$\mathcal{Z}_{i-}$	Negative half-zone of zone $\mathcal{Z}_i$
$\mathcal{R}^{i+}_{j[k]}$	*Sub-zone* located at distance $j\lambda \pm \lambda/2$ from relay node (V_i) with priority-k
T_{SIFS}	Minimum time required to detect an ongoing transmission
T_{data}	Length/duration of the packet transmission
Δ_{sess}	Session duration
Δ_{seq}	Transmission sequence duration
d	Vehicle relative distance from the relay node zone
$\mathcal{O}_{\text{sess}}$	Session order
$k_{\max} = 5$	Lowest priority order in a sequence
Q_u (resp. Q_v)	Queue for packets of type-u (resp. type-v)i.e. packets from nodes of half-zone $\mathcal{Z}_{u+}$ (resp. $\mathcal{Z}_{v-}$)
NAV$[j, k, T]$	Access time relatively to T at which the vehicle in the jth sub-zone with *priority-k* is allowed to attempt transmission
$v = v(T)$	Rank of the ending transmission sequence
Δ_{mac}	Duration of the multiple access (mac) phase
Δ_{bro}	Duration of the broadcast (bro) phase
s	Function attributing a transmission sequence to a sub-zone
Δ_{i+}	Time after which the dissemination is completed
$\mathcal{Z}_{u+\cup v-}$	Extended half-zone) resulting of the superposition of half-zones $\mathcal{Z}_{u+}$ and $\mathcal{Z}_{v-}$
q	Number of sub-zones in inter-zone $\mathcal{Z}_{u+} \cap \mathcal{Z}_{v-}$
$S^{\mathcal{S}^{1**}_{u+\cap v-} \cap \mathcal{S}^{1*}_{v-}}_{\text{min}}$	Minimum conflictual-sequence during the first session
$\mathcal{S}_x$	Set of all the n_x information-sequences involving packets of type-x ($x = u, v$) excluding packets emitted from the inter-zone
$\mathcal{S}$	Set of all the n information-sequences during the first session
$f^{\mathcal{S}_x}_x$	Function that gives the number of packets of type-x present in the Q_x queue at the end of the last information-sequence of $\mathcal{S}_x$

VII. Numerical analysis of MAP

Let us consider an extended half-zone with the inter-zone containing at least one sub-zone. Let us assume that we have $R = 100$ sub-zones per half-zone. We evaluate η, the ratio of the number of broadcast-sequences required at the end of the first MAP session to the number of packets at the beginning of the dissemination process, with respect to the distribution of the active sub-zones within the network. Let δ be the number of inactive sub-zones between two consecutive active sub-zones, and κ the number of sub-zones within the inter-zone.

A. Case 1: $\delta = 1$

In this case, we assume that two consecutive active sub-zones are separated by only one inactive sub-zone ($\delta = 1$). The results are shown in Fig. 5. The red curve with stars (*) represents the case where the number of sub-zones within the inter-zone is even and the other curve is for the case when this number is odd. A considerable difference in the number of broadcast-sequences still required at the end of the first session can be observed. The reason is that for an even number, the number of exposed sequences with the same rank is higher compared to the case of an odd number, resulting into a high number of PLNC-based transmissions. In addition, for the case where κ is even, we observe that the performance of MAP varies depending on whether κ is lower or higher than $R/2$. When $\kappa \leq R/2$, η decreases when κ increases, and conversely, when $\kappa > R/2$, the ratio η increases when κ decreases.

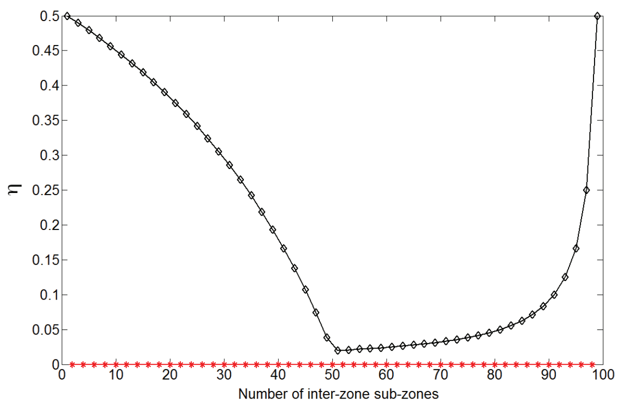

Fig. 5: Ratio η with respect to κ when $\delta = 1$. The upper curve is when κ is odd and the bottom one is when κ is even.

B. Case 2: $\delta = 0$

In this case, we assume that the number of inactive sub-zones between two consecutive active sub-zones is $\delta = 0$. The results are shown in Fig. 6. We observe that no broadcast-

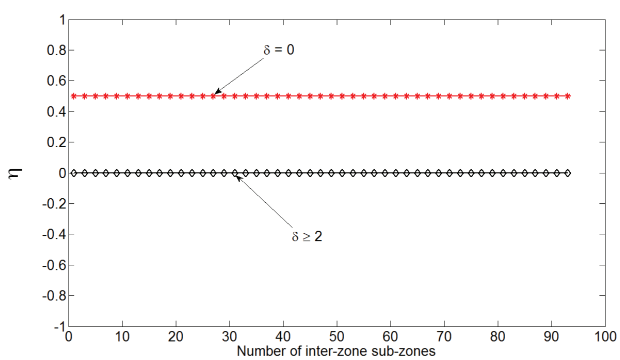

Fig. 6: Ratio η with respect to the number of sub-zones within the inter-zone. Cases where $\delta = 0$ (up) and $\delta \geq 2$ (bottom).

sequence takes place within the first session, and given that the MAP implements network-coding during broadcast phases, the total $N = 2N_u = 2N_v$ packets required to be forwarded will be reduced to $N/2$ network-coded packets. Hence $\eta = 0.5$.

C. Case 3: $\delta \geq 2$

In this case, we assume that the number of inactive sub-zones between two consecutive active sub-zones is $\delta \geq 2$. The results are shown in Fig. 6. We observe that the presence of an additional empty sequence between two information-sequences reduces the number of broadcast-sequences required at the end of the first session. All broadcast-sequences take place during the first session since the transmissions during the next session are transmissions from inter-zone nodes that did not transmit during the first session.

VIII. Conclusion

In this paper, we proposed and analyzed MAP, a vehicular PLNC-based MAC protocol. MAP implements two simple modes of forwarding to guarantee fast all-to-all dissemination in multi-hops VANETS. It is a decentralized deterministic and dynamic priority-based wireless medium access protocol which allows an effective use of PLNC in large-scale VANETS. MAP considers the wireless medium access and the way information is forwarded over the network, to ensure fast and reliable transmissions. It does not require any centralized node, nodes can join or leave the dissemination process anytime, and the presence of inactive sub-zones improves significantly the dissemination completion time. MAP can be adjusted depending on the type of application and thus can be used for different dissemination scenarios. With MAP, we achieve faster all-to-all dissemination in multi-hop VANETS.

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