Reliable Broadcasting in VANETs using Physical-Layer Network Coding

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***Abstract*—In this paper, we present a PNC-based MAC protocol for VANETs (VPNC-MAC) which makes use of the PNC to ensure efficiency and reliability of periodic beacon transmissions in VANETs. The VPNC-MAC protocol basically consists on two phases: a setup phase and the heartbeat packet exchange phase. During the setup stage, VPNC-MAC uses a location-based OFDMA signaling technique to guarantee a quick and non bandwidth consuming setup. In addition, the packet exchange phase in VPNC-MAC contains two periods of variable and adjustable length. The fist period is a guaranteed time slot period, called the VPNC-MAC session, in which the nodes exchange their packets using PNC. The second period is a contention period reserved to nodes unable to transmit during the VPNC-MAC session. The simulation results shows that the VPNC-MAC protocol outperforms the optimal CSMA (ideal TDMA) in terms of capacity of transmissions supported within a fixed duration, and overall packet reception rate.**

I. Introduction

Vehicular Ad hoc Networks (VANETs) play an important role in road safety by including vehicle cooperation and exchange of time-sensitive information, including location, speed, and acceleration, thus enhancing each vehicle awarness of its surroundings.

To make this paradigm a ubiquitous reality, IEEE has recently adopted the Dedicated Short-Range Communication (DSRC) radio technology under a new standard for vehicular networks, known as Wireless Access in Vehicular Environment (WAVE)/802.11p protocol [1]. In fact, all vehicles in a near future are expected to incorporate the DSRC technology. Basically, DSRC [2] operates at the 5.9 GHz band divided into seven 10 MHz channels (among which one channel, the control channel CCH, is reserved for system control and safety-related messages, and up to six channels, the service channels SCHs, are used to transmit non-safety data) with a 5 MHz guard band. DSRC utilizes the Orthogonal Frequency Division Multiplexing (OFDM) technique to support low latency wireless data communications among vehicles and between vehicles and infrastructure up to few hundred meters. Vehicles access the wireless medium using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA or simply CSMA) together with the Enhanced Distribution Coordination Function (EDCF) to ensure Quality of Service (QoS) among emergency and routine safety messages. However, due to bad link qualities, transmission range degradation, and high collision probability in dense CSMA-based VANETs, the standard fails to ensure reliable and efficient broadcasting in those conditions, which is a requirement for safety-based applications.

Our objective in this work is to address these issues for the particular scenario of periodic safety-beacon transmissions within the CCH, with the use of techniques based on the Physical-Layer Network Coding (PNC) [3]. More specifically, our goal is to provide fundamental elements of answer to the following questions:

- How to dynamically and efficiently schedule transmissions (in terms of time/bandwidth consumption) so that we approach the upper bound capacity of CSMA of possible transmissions within a time interval?
- How to take advantage of simultaneous transmissions (collisions) and relaying in PNC to improve the reliability and the packet reception rate (PRR) in VANETs?
- Given the mobility and the position of vehicles in the network, how to find a good (the best) relay at a given time so that the use of PNC is (quasi-) optimal, and the improvements targeted in the previous question are obtained?

As a way to answer these questions, we propose a PNC-based MAC protocol for VANETs, which we refer to as the VPNC-MAC protocol or simply VPNC-MAC. VPNC-MAC is designed to operate under the WAVE standard, so that VPNC-MAC-based devices are compatible with WAVE-based devices. However, since VPNC-MAC makes use of the PNC which is a non standard technique based on interference, pure WAVE-based devices will not be able to decode PNC signals but will still be able to understand one-hop non relayed messages from VPNC-MAC-based devices.

Our contribution in this paper is threefold:

- First, based on available position/speed information of nodes in a zone, we propose a simple technique where the node with the best coverage in terms of number of neighbors within the transmission range is chosen as the relay node for those nodes for a given time interval.
- Second, to efficiently schedule PNC-based transmissions while consuming as little as possible bandwidth during the setup phase, we incorporate in the VPNC-MAC setup phase a location-based Orthogonal Frequency Division Multiple Access (OFDMA) scheme.
- And finally, we make PNC transmissions effective in the VPNC-MAC session to ensure reliability and efficiency during the periodic safety-beacon exchange procedure. Further-

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more, to deal with the transmissions unable to be performed within the VPNC-MAC session, we adopt in VPNC-MAC the presence of a contention period of dynamic and predetermined duration.

The remainder of the paper is organized as follows. Section II presents some related works. In Section III, the system model is described with the main assumptions considered. The VPNC-MAC protocol is detailed in Section IV, and the results of its performance analysis are presented in Section V. Finally, Section VI concludes this work while highlighting future directions.

II. Related Work

Reliable broadcasting is an important issue in VANETs. The probability of successful reception of a message by a receiver node strongly depends on many factors among which the presence of interferences in the communication range, the distance between the sender and the receiver, the quality of the communication links, and so on. For instance, for a given transmission power, and assuming no hidden terminal transmission scenario, the reception rate of nodes within 100 meters from the transmitter is many times higher than ($\geq 90\%$) the reception rate of nodes placed at about 300 meters from the transmitter node ($\leq 20\%$) [4]. In [4], the authors propose a piggybacked cooperative repetition mechanism to improve reliability of broadcasted messages in VANETs. They showed that their proposed scheme achieves over 90% reception rate at distances up to 200 meters from the sender node. In addition to using CSMA/CA which is shown to have a poor performance in overloaded networks due to dropped packets and high probability of collisions, the proposed piggybacked scheme might suffer from larger bandwidth consumption.

To overcome this bandwidth usage issue, the authors in [5] investigated the use of network coding in improving the bandwidth efficiency of retransmission-based recovery in vehicular safety communication. They showed that the bandwidth usage can be reduced by about 62% while increasing the reception rate by up to 20%. Although the bandwidth usage is reduced compared to [4], there is still some bandwidth wastage due to unecessary retransmissions, and the issues caused by the use of CSMA in highly dense networks are still present.

The authors in [6] propose the use of the decentralized self-organizing TDMA (STDMA) MAC protocol [7] in which each node follows four different phases (initialization, network entry first frame and continuous operation), and which relies on the position information sent by the nodes. Although the use of coordinated transmissions in STDMA considerably reduces the presence of collisions, STDMA still lacks to ensure reliability of transmissions.

In [8], the authors propose a OFDMA-based MAC protocol for VANETs where nodes dynamically organize themselves into clusters, each cluster using a set of subcarriers that are different from the other clusters ones in order to mitigate the hidden terminal problem and while reducing the end-to-end broadcasting time delay. However, in each cluster, the problem of reliability is not explicitly addressed.

The authors in [9] propose the VDA (Vehicular Deterministic medium Access) protocol which uses both a contention period and a contention free period (CFP). In the CFP, VDA acts as a TDMA scheme by letting requesting vehicles to access the wireless medium at specific time slots to transmit emergency messages.

An attempt to make an effective use of PNC is done in [10]. The authors present the PNC-MAC protocol which modifies the IEEE 802.11 request-to-send/clear-to-send (RTS/CTS) MAC protocol. In PNC-MAC the relay requests specific nodes to participate in the PNC process. The frequent use of RTS/CTS message increases the end-to-end transmission delays and renders this protocol inefficient for highly dynamics VANETs.

Despite some interesting results observed for very specific applications in these related works, they fail to ensure simultaneously high reliability, low transmission delay and scalability for various scenarios. On the contrary, the PNC-based MAC protocol proposed in this work takes advantage of the distributed and simultaneous access to the wireless medium to guarantee efficiency and reliability of transmissions in VANETs.

III. System model and assumptions

We consider a 1-D straight zone of length $L \leq R$ (R being the detection range) such that all the vehicles considered are in the detection range of each other (see Fig. 1). The detection range or (carrier-) sensing-range defines the zone where vehicles can detect ongoing transmissions. All the vehicles are assumed to have the same transmission range and sensing range.

For simplicity of presentation, we do not consider the hidden terminal problem in this work.

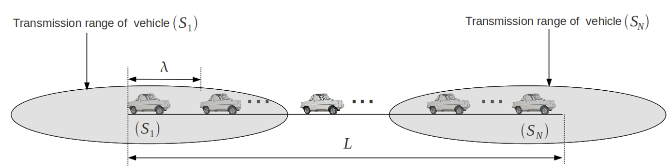

Fig. 1: 1-D road of length L. The vehicles are assumed to be λ-equidistant.

The vehicles operate (transmit and receive) only in the control channel CCH (5.885GHz$-$5.895GHz) in the omnidirectional half-duplex mode, and they move in the same direction. The vehicles can use either VPNC-MAC or DSRC/802.11p protocols to communicate. We assume that all the vehicles are equipped with the global positioning system (GPS) for positioning and time synchronization to the Coordinated Universal Time (UTC), so that when VPNC-MAC is used, the devices are assumed to be synchronized in time, phase and frequency. Synchronization is further facilitated since the broadcasting of periodic beacons takes place only within the synchronized interval defined by the WAVE standard. Furthermore, without loss of generality, and since we are interested solely in beacon messages, we assume that the beacons are periodically and synchroneously generated at the nodes. At the receiver nodes, when PNC is used, we assume that by means of technique such as the blind decoding technique proposed in [11], the content of each individual packet is determined.

IV. The VPNC-MAC protocol

Basically, the VPNC-MAC protocol is a self-organized protocol in which the node having the better coverage of the zone in terms of higher number of nodes within its transmission range (details are given further) ensures the role of coordinator for a predetermined amount of time. During a setup procedure, the nodes exchange with the relay node very short signaling messages using a position-based OFDMA scheme that avoids collisions while consuming a negligeable amount of bandwidth (or time). During this phase, the relay node assigns to the nodes by pair specific time slots to transmit using PNC. In VPNC-MAC, a contention period of variable length is also reserved for nodes unable to transmit during the guaranteed period if some nodes do not get transmission slots assigned.

Globally, VPNC-MAC is a two-step procedure: (1) the VPNC-MAC setup, and (2) one or more VPNC-MAC sessions including contention periods (CP).

A. The relay node selection

The relay node in VPNC-MAC is chosen according to a specific relay node selection mechanism. Basically, the problem of the relay node selection is a routing problem. In VPNC-MAC protocol, the relay node is selected such that it improves the message broadcast given the communication issues in VANETs using the standard IEEE 802.11p. In other words, the relay node must have the best coverage in term of transmission range, with a low delay in terms of remaining time before its timer to transmit the current heartbeat message expires.

Therefore, for a given node (S_i), its contention window CW_i in VPNC-MAC is given by

$$CW_i = k_1 R_d(i) + k_2 R_\tau(i), \tag{1}$$

where, k_1 and k_2 are some unitless scaling factors used to adjust the contention window, and $R_\tau(i)$ and $R_d(i)$ are unitless metrics to be determined. $R_\tau(i)$ is based on the remaining time, τ_i, before the node's timer to transmit its current heartbeat message expires. A simple way to determine $R_\tau(i)$ is to set it inversely proportional to τ_i. That is,

$$R_\tau(i) = \frac{c_\tau}{\tau_i}, \tag{2}$$

where c_τ is a scaling factor in second (s). $R_d(i)$ is related to the relative distance of the node (S_i) to the other nodes within its sensing range. $R_d(i)$ also depends on the transmission range R_t. Given N and N_i, respectively the number of nodes within the sensing range and the transmission range of (S_i), $R_d(i)$ can be computed as

$$R_d(i) = c_1(N - N_i) + c_2 \max_{j \in \mathcal{N}_i} \{d_{ij}\}, \tag{3}$$

where, $\mathcal{N}_i$ is the set of nodes within the transmission range of (S_i), d_{ij} is the Euclidean distance between nodes (S_i) and (S_j). c_1 is a scaling factor without unit, and c_2 a scaling factor in (1/m).

Therefore, the relay node in VPNC-MAC corresponds to the node which has the minimum contention window, that is

$$CW_{\text{Relay}} = \min_{i \in \mathcal{N}} \{CW_i\}, \tag{4}$$

where $\mathcal{N}$ is the zone considered which corresponds to the set of vehicles within the sensing range of node (S_i). In previous work, it has been proven that all the nodes have the same estimation of $\mathcal{N}$; this assumption makes sense only if a node does not belong to more than one zone at the same instant, and if the transmissions belonging to adjacent zones are distinguishable [8].

B. The packet exchange using VPNC-MAC

1) VPNC-MAC setup: Once the timer has expired, if no transmission is detected, the node broadcasts its VPNC-Cooperation ReQuest (VPNC-CRQ) message to its neighbors to invite them to take part to a VPNC-MAC packet exchange procedure. The structure of the VPNC-CRQ frame is shown in Fig. 3.

Bytes:	2	2	6	4
VPNC-CRQ	Frame Control	Duration ID	Transmitter address	FCS

Bytes:	2	2	6	M	2	4
VPNC-TSQ	Frame Control	Duration ID	Transmitter address	Active subcarrier/batch ID	Duration of the CP	FCS

Fig. 3: Structure of the frames in VPNC-MAC.

After receiving a valid VPNC-CRQ message (if no valid VPNC-CRQ frame has been detected due to collision or for some other reason, another contention round is performed), a node interested in cooperation will respond by sending a very short message called the VPNC-Cooperation RePly (VPNC-CRP) message, enough to be carried by a single subcarrier in OFDM. The content of the VPNC-CRP message is the same for each node and is known by everyone (like the pilot symbols). The role of the VPNC-CRP is simply to activate specific subcarriers so that the receiver can derive the position of the senders. To prevent unwanted collisions with other possible transmissions, VPNC-MAC makes use of a location-based OFDMA procedure. Indeed, the selection of the subcarrier ω_j among the available frequencies $\left\{\omega_{-F/2}, ..., \omega_{-2}, \omega_{-1}, \omega_1, \omega_2, ..., \omega_{F/2}\right\}$ at which a node transmits its VPNC-CRP signaling is based on its position relatively to the position of the relay node. In fact, given the distribution of the nodes in the zone, that is, knowing the relative distance λ between two consecutive nodes, if the distance $d(u, \text{relay})$ between the relay node and the node (S_u)

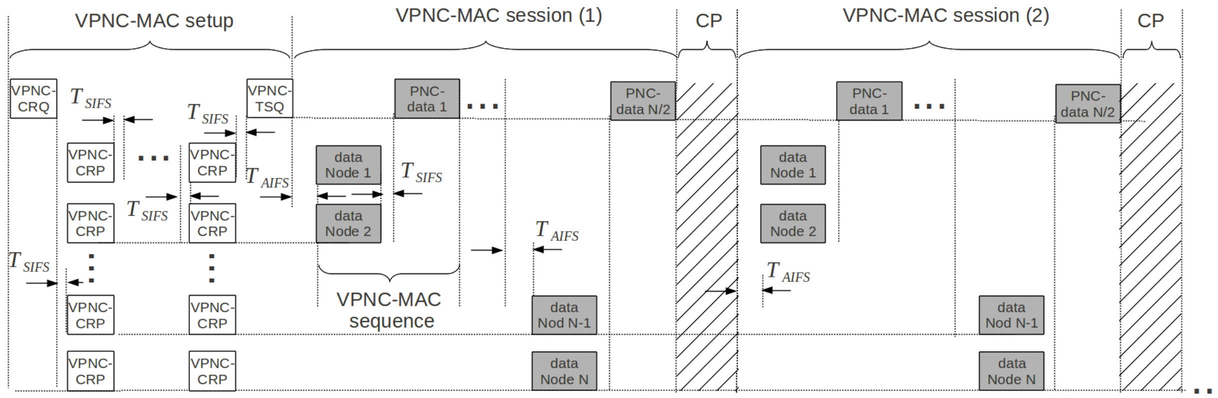

Fig. 2: Packet exchange using VPNC-MAC protocol.

is such that $\lambda(i-\frac{1}{2}) < d(u, \text{relay}) < \lambda(i+\frac{1}{2})$, the node will assume to occupy the position i (resp. $-i$) if it is in front of (resp. behind) the relay node (the positive direction is the direction of the vehicles). Hence, a node with position i (resp. $-i$) will transmit on subcarrier ω_j (resp. ω_{-j}) at the batch $\lceil \frac{2i}{F} \rceil$, where

$$j = \begin{cases} i - \frac{F}{2}\lfloor \frac{2i}{F} \rfloor & \text{if } i - \frac{F}{2}\lfloor \frac{2i}{F} \rfloor \neq 0, \\ \frac{F}{2} & \text{if } i - \frac{F}{2}\lfloor \frac{2i}{F} \rfloor = 0. \end{cases}$$

Only the nodes which received the VPNC-CRQ can send a VPNC-CRP signal. The total number of batches per VPNC-MAC session ($\lceil N_{\text{max}}/F \rceil$) depends on both the maximum number of nodes in the zone, N_{max}, that a zone can support, and the maximum number of nodes that can transmit within a batch (this number corresponds to the maximum number of subcarriers, F, per OFDM symbol). The duration between the end of a batch b and the begining of the batch $b+1$ corresponds to the short interframe space (SIFS) T_{SIFS}.

Therefore, the duration of the VPNC-MAC setup can be expressed by

$$\begin{aligned} T_{\text{VPNC-setup}} &= T_{\text{VPNC-CRQ}} + T_{\text{VPNC-TSQ}} + T_{\text{SIFS}} \\ &+ \lceil N_{\text{max}}/F \rceil (T_{\text{VPNC-CRP}} + T_{\text{SIFS}}). \end{aligned} \quad (5)$$

The detection of VPNC-CRP signals is done in a similar way as in [12]; it simply consists of detecting active subcarriers by means of higher FFT sizes (256 point FFT for example) to leverage the subcarrier leakage problem, although we assume in this work an ideal OFDM system.

Based on the reception of the VPNC-CRP signals, the relay node notifies the senders through the broadcast of a VPNC-Transmission SeQuence (VPNC-TSQ) packet. The structure of the VPNC-TSQ frame is shown in Fig. 3. M indicates the number of active subcarriers detected, it corresponds in bytes to the size of the field *active subcarrier/batch ID*. This field contains the subcarrier ID of the nodes whose subcarrier has been successful detected. In the next field *duration of the CP*, the duration of the CP is indicated. The relay node sets this duration according to the number of inactive subcarriers detected and the maximum available time.

2) VPNC-MAC session: Upon the reception of the VPNC-TSQ frame, each node waits for its allocated VPNC-MAC sequence to send its packet. The VPNC-MAC sequence basically corresponds to the standard two-step transmission in PNC [3]. If a node does not identify its subcarrier ID, it waits for the contention period to transmit its packet. The duration between two consecutive VPNC-MAC sequence corresponds to the arbitrary inter-frame space T_{AIFS}. Let u be a VPNC-MAC sequence order, a node scheduled to transmit within that period has to wait for a duration of $T_{\text{wait}(u)}$, with

$$T_{\text{wait}(u)} = uT_{\text{AIFS}} + (u-1)T_{\text{VPNC-seq}}, \quad (6)$$

and $T_{\text{VPNC-seq}}$ being the duration of a VPNC-MAC sequence. $T_{\text{VPNC-seq}}$ is given by

$$T_{\text{VPNC-seq}} = T_{\text{SIFS}} + 2T_{\text{data}}, \quad (7)$$

where T_{data} is the duration of the data (physical-layer headers and MAC layer headers included).

3) The Contention Period: In the contention period, the nodes that did not take part in the VPNC-MAC session can compete to send their packets. This period is also the occasion for other new nodes to send their packets and join the network. However, the duration of the contention period depends on the number of nodes wishing not or unable to transmit during the VPNC-MAC session, and more important to the duration Δ during which the network is assumed to be stable.

Let us assume that N_{CP} nodes that did not take part in the VPNC-MAC session compete which each other. Therefore, the duration of the CP T_{CP} is given by

$$T_{\text{CP}} = N_{\text{CP}}(T_{\text{AIFS}} + T_{\text{data}}). \quad (8)$$

The diagram of the packet exchange is shown in Fig.2.

V. Numerical Results

In this section, we analyze and compare the performances of the VPNC-MAC protocol with those of the optimal CSMA protocol (no backoff time is consumed and no collision occurs). We consider the system described in Section III. The length of the zone considered is 1000m, and the nodes are averagely equidistant of $\lambda = 10$m. The simulations are conducted in Matlab in two steps. First, we analyze the upper bound of the number of nodes that can transmit when either the optimal CSMA or the VPNC-MAC are used. Second, we analyze the packet reception rate (PRR) of each protocol for different settings. Table I lists the simulation parameters used in this work. For our simulations, we choose the parameter values based on the specifications of 802.11p [1]. Therefore, The heartbeat packet (headers includes) is a 300 bytes frame containing the MAC id timestamp and position/speed information derived from the onboard GPS. In VANETs, the heartbeat messages are sent a number of times in a regular synchronized interval of 100ms corresponding to the minimum generation rate (or packet frequency) f of 10Hz. For purpose of analysis, we consider f in the range of $[10\text{Hz}, 20\text{Hz}, ..., 50\text{Hz}]$. To evaluate the impact of the transmission range R_t on the performances of the protocols, we consider the range $[100m, 1000m]$ of possible values of R_t. For each value of R_t, we consider different possible probabilities of successful reception in the range $[10\%, 70\%]$. We consider $\Delta = 1\text{s}$.

TABLE I: Parameters of simulation

Parameter	Value
Length of the road (L)	1000m
Average distance between vehicles antennas (λ)	10m
Sensing range (R)	1000m
Transfer rate	6Mbps
AIFS	34μs
SIFS	16μs
Packet length	300 bytes
Packet exchange duration (Δ)	1s
Packet frequency (f)	10Hz$-$50Hz
Transmission range (R_t)	100m$-$1000m
Probability (p) of successful reception beyond R_t	$10\% - 70\%$
Total number of subcarriers (F)	52

A. Analysis results of the maximum number of nodes/transmissions supported by each protocol

In this subsection, we evaluate numerically the upper bound of the capacity of nodes or transmissions that can be supported by both optimal CSMA and VPNC-MAC protocols. In the first scenario, we assume that only the relay node transmits its packets during the CP. For different values of f, we determine the maximum number of nodes N_max. The results are shown in Fig. 4. We can observe that for low frequencies f, the capacity supported by VPNC-MAC is slightly better than the optimal CSMA one, since the number of transmitter is high. The reason is that in a VPNC-MAC sequence, the time difference between the two PNC stages (T_SIFS), which corresponds to the transmission of two packets, is smaller that the time difference between the transmission of two packets when the optimal CSMA is used (T_AIFS). However, this difference is little when the packets are transmitted with high frequency.

In the second scenario, we consider different fraction of nodes transmitting in the CP, and we set the number of packets transmitted by each node to $f = 10$Hz. The maximum number of nodes that can transmit without collision in this case is shown in Fig. 5. We observe that when the number of contending nodes in the CP is low, the high capacity of the VPNC-MAC compared to the upper bound of the optimal CSMA is still noticeable. But, as the number of contending nodes increases, the capacities of both the VPNC-MAC and the optimal CSMA become equal.

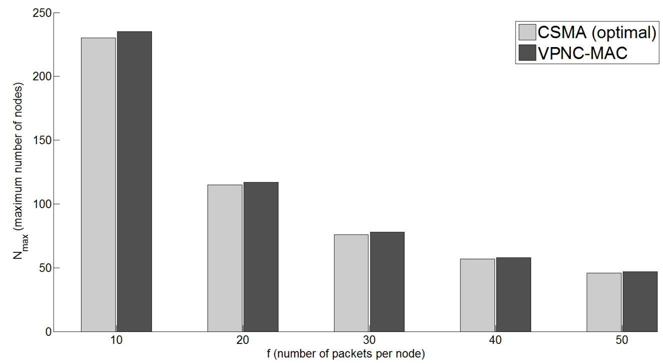

Fig. 4: Maximum number of nodes N_max with respect to the number of packets f that can be transmitted by each node ($\Delta = 1\text{s}$).

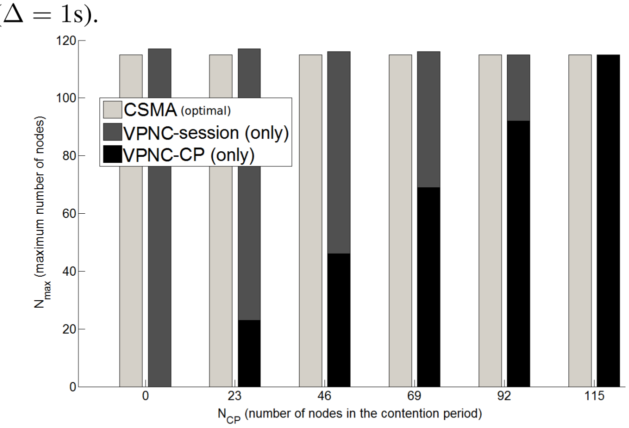

Fig. 5: Maximum number of nodes N_max with respect to the number of nodes transmitting in the CP in the VPNC-MAC protocol. The number of packets that each node transmits during $\Delta = 1\text{s}$ is $f = 10$Hz.

B. Analysis Results of the PRR

In this part, we consider an underloaded network; that is the total number of packets to be transmitted by all the nodes is less than the maximum number of transmissions supported by either VPNC-MAC or optimal CSMA. More explicitly, considering the average distance between vehicles and the length of the zone, we set the number of vehicles to 100 and the number of packets transmitted by each vehicle to 20Hz.

We determine the PRR of the network when either the VPNC-MAC or the optimal CSMA is used, with respect to the ratio r of the transmission range to the sensing range. We also assume in this case that only the relay node transmits its own packets within the CP, although the relaying is performed during the VPNC-MAC session. We further consider three cases depending on the probability p of successful reception beyond the transmission range R_t. The results are shown in Fig. 6. The determination of the relay node in this case shows that it is the node at the 'center' of the zone since the nodes are uniformly distributed in the zone; it has a better coverage of the network than the other nodes. We observe that when the ratio $r \geq 0.5$, the $\text{PRR}_{\text{VPNC}} = 1$ is maximum whatever the probability p. When $r < 0.5$, the PRR of the VPNC-MAC is still better than the optimal CSMA one, and increases as the probability p increases. VPNC-MAC takes advantage of its two-hop transmissions ability to achieve better reliability within the overall sensing range. However, we notice that the performances of VPNC-MAC over the optimal CSMA depends on a particular value, r_{o}, of the transmission range to sensing range ratio. Indeed, under the ratio $r_{\text{o}} \approx 0.4$, the optimal CSMA has a better performance than VPNC-MAC. The reason is that the transmission range is so low compared to the sensing range ($r < 0.4$) that relaying some transmissions becomes inefficient. In addition, and more important, to capture only the effect of relaying, we have considered in the results of the PRR of the VPNC-MAC protocol, only the successful packets decoded from the PNC-based collision packets at the relay node. The packets received without collision or blind-decoded directly at the nodes, case which is highly probable when the transmission range is too low compared to the sensing range, are not considered. When considered, the results (not shown in this paper, due to lack of space) of the VPNC-MAC PRR outperforms the optimal CSMA for any ratio.

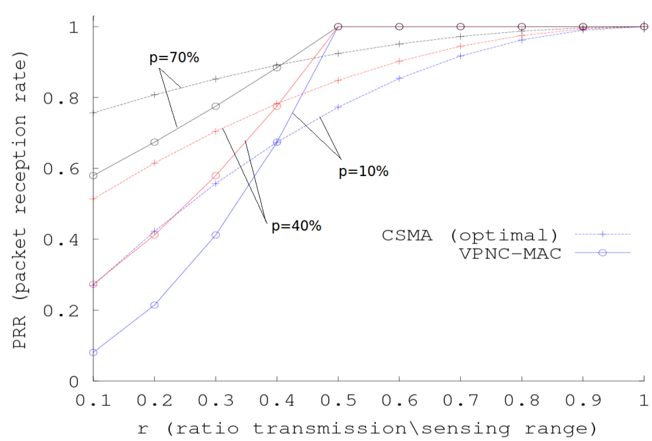

Fig. 6: PRR with respect to the ratio of the transmission range to the sensing range.

However, these results suggest that it is recommended for the nodes to select the period within which to transmit, depending on the quality of the transmission links. When the ratio of the transmission range to the sensing range is less than a particular value r_o, transmissions of packets can be performed without relaying but with a deterministic approach which has a better performance than the conventional CSMA/CA in dense networks.

VI. Conclusion and Future Work

In this paper we introduced and analyzed a Vehicular PNC-based MAC protocol (VPNC-MAC). VPNC-MAC makes use of two periods, a reserved period called the VPNC-MAC session in which the nodes transmit using PNC, and a contention period used by nodes who could not get assigned slots. The analysis results showed that, the use of PNC in VPNC-MAC ensures a better reliability compared to the optimal CSMA.

However, VPNC-MAC relies on time and frequency synchronization which is a primary issue in highly dynamic wireless network communications, especially when OFDM-based techniques are involved. Therefore, as future direction, the authors will try to provide significant elements to improve the performances of VPNC-MAC when time and frequency synchronization errors are considered.

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