Benchmarking the Cooperative Awareness Service at Application Layer with IEEE 802.11p and LTE-PC5 Mode-4

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***Abstract*—Vehicular communications hold the promise of disrupting mobility services and supporting the mass adoption of future autonomous vehicles. Regulators have set aside specific spectrum at the 5.9 GHz band to support Intelligent Transport Systems (ITS) safety applications, for which a world-wide adoption of a standardized radio technology is a key factor to deliver on this promise. Two technologies are currently positioned to begin its commercial path, IEEE 802.11p and LTE-PC5 Mode-4. The main differences between these technologies lie on the design of their channel access mechanisms. This paper provides an analysis of the impact that the Medium Access Control (MAC) mechanisms included in 802.11p and LTE-PC5 Mode-4 will have on the performance of the applications using the Cooperative Awareness Service, applying two new application-level metrics used by safety applications: Neighborhood Awareness Ratio and Position Error. We have found that, even with an equivalent physical layer performance, the MAC layer of LTE-PC5 Mode-4 will mostly outperform the MAC layer of IEEE 802.11p (or its not yet ready enhanced version 802.11bd). However, IEEE 802.11p/bd results in slightly better vehicle positioning accuracy at lower distances.**

Keywords—V2X, C-V2X, LTE-PC5 Mode-4, DSRC, 802.11p, 802.11bd, Cooperative Awareness

I. INTRODUCTION

The vehicular communications (V2X: Vehicle-to-Everything) landscape has experienced a shake up with the advent of two competing radio technology families supported by the IEEE and the 3rd Generation Partnership Project (3GPP). The IEEE pioneered the first radio technology aimed at V2X communications with the IEEE 802.11p standard published in 2010, also known as Direct Short-Range Communications (DSRC). This technology operates with channels of 10 MHz bandwidth in the Intelligent Transport Systems (ITS) band at 5.9 GHz, and is based on the IEEE 802.11a Physical (PHY) layer and the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Medium Access Control (MAC) mechanism. Until recently, 802.11p was considered the de-facto radio technology to support the day-1 vehicular safety services defined by the European Telecommunications Standards Institute (ETSI) ITS-G5 suite in Europe and the Wireless Access in Vehicular Environments (WAVE) in the US [1]. Safety services are based on issuing driver alerts upon potentially dangerous situations, and have been extensively validated by Original Equipment Manufacturers (OEMs) around the world in field trials using 802.11p, reporting a sufficient performance as long as the channel congestion is not severe [2].

The 3GPP specified in Release 14, in 2017, an evolution of the Long-Term Evolution (LTE) PC5 interface, known as Cellular V2X (C-V2X), which in its Mode-4 variant, can operate at the ITS 5.9 GHz band in an infrastructureless decentralized manner, thus supporting day-1 safety services. A clear technical advantage of LTE-PC5 Mode-4 over IEEE 802.11p is a more advanced physical layer, which results in improved range under high mobility conditions, as verified in [3]. The LTE-PC5 ecosystem of chipset and component providers is however not as mature as the 802.11p one, which has resulted in a heated debate among regulators across the world about the technology of choice to support day-1 safety services. A prominent example of this debate is the C-ITS Delegated Act [4] from the European Commission, which in its first version only supported IEEE 802.11p, and was later pushed back by the telecommunications industry.

On the technical side, both the IEEE and the 3GPP, continue to enhance their support for vehicular communications. The IEEE launched the 802.11bd working group, which will update the physical layer of 802.11p to the one used in 802.11ac (Very High Throughput) [5]. On the other hand, the 3GPP defined in Release 16 C-V2X extensions for the 5G-New Radio technology, known as NR-V2X. This technology does not target day-1 safety services in the ITS band (5.9 GHz), but will focus on value added services using licensed spectrum, such as teleoperated driving or platooning [5]. Therefore, the candidate technologies to support day-1 safety services are going to be IEEE 802.11p and its successor 802.11bd, and 3GPP LTE-PC5 Mode 4. Recent works like [6] have analysed the physical layer performance of 802.11bd against LTE-PC5 Mode-4 and NR-V2X, showing that 802.11bd is able to deliver similar Packet Reception Ratios (PRR) as LTE-PC5 Mode-4 and NR-V2X for moderate distances (< 250 meters) when using small packets and robust Modulation and Coding Scheme (MCS), although the throughput is smaller. Hence, we claim that for day-1 safety services, at moderate distances, the decisive factor between the two technologies will come through their channel access mechanisms, which become critical especially under high road congestion.

ITS safety services are based on the periodic broadcast of small data packets that convey status information to neighboring vehicles. A prominent example is the

Cooperative Awareness Message (CAM) which reports the position, speed and direction of a vehicle with a periodicity of 1-10 Hz. Safety applications, such as collision avoidance, are built analysing in each vehicle the CAM messages received from neighboring vehicles.

Previous works in the state of the art have analysed the performance of IEEE 802.11p and LTE-PC5 Mode-4 focusing on MAC level metrics, but most obviate the impact of these technologies on the application layer. For instance, focusing specifically on the Cooperative Awareness (CA) service, the authors in [7] develop an analytical model to evaluate the performance of IEEE 802.11p and LTE-PC5 Mode-4, concluding that IEEE 802.11p performs better at shorter distances and LTE-PC5 Mode-4 at longer distances, due to its higher robustness. In [8] authors introduce the Neighborhood Awareness Ratio (NAR) as a novel metric to evaluate the efficiency of the Cooperative Awareness Service over IEEE802.11p, and present results of large-scale trials and simulations performed in the context of the DRIVE-C2X project [9]. On the other hand, authors in [10] consider an ideally modified IEEE 802.11p with a PHY layer providing the same performance as that of LTE-PC5 to be able to analyse the MAC layer without the influence of the PHY layer, assuming that, in a near future, 802.11p will be substituted by 802.11bd. They analyse the performance of LTE-PC5 Modes 3 and 4 against 802.11p in terms of PRR and update delay. This work concludes that LTE-PC5 Mode 3 always outperforms 802.11p, but when the equivalent PHY is considered, a similar performance is observed for LTE-PC5 Mode 4 and 802.11p.

The main contribution of this present paper is an analysis based on packet level simulations of the impact of the MAC layer mechanisms included in 802.11p and LTE-PC5 Mode 4 on the performance of applications that use the CA service, which is measured introducing two new application layer metrics: NAR and Position Error. Using the same assumptions as [6] and [10], which assume that the current enhancements being discussed in IEEE 802.11bd will result in an equivalent PHY layer performance as LTE-PC5, we analyse the impact of the MAC level mechanisms in 802.11p/bd and LTE-PC5 Mode-4 at the application layer of the CA service, independently of the PHY layer. This paper is structured as follows. Section 2 introduces the channel access mechanisms defined in 802.11p/bd and LTE-PC5 Mode-4. Section 3 describes the CA service and the Key Performance Indicators (KPIs) we use to evaluate it. Section 4 presents a simulative evaluation describing the impact of 802.11p/bd and LTE-PC5 Mode-4 on the performance of the CA service at application layer. Finally, section 5 summarizes and concludes the paper.

II. IEEE 802.11P AND LTE-PC5 MODE-4 INTRODUCTION

A. IEEE 802.11p, IEEE 802.11bd

IEEE 802.11p is based on the widely used IEEE 802.11a, or OFDM (Orthogonal Frequency - Division Multiplexing) PHY in standard IEEE Std 802.11-2020, which removes the requirement of having to be associated to a Basic Service Set (BSS) to be able to transmit or receive data, this is why IEEE 802.11p is called "Outside the Context of a BSS" (OCB).

The PHY layer uses the same modulation and coding schemes as IEEE 802.11a, but the channel bandwidth is 10 MHz instead of 20 MHz. Therefore, data rates are halved, beginning at 3 Mbps and reaching up to 27 Mbps, being 6 Mbps the default data rate (QPSK modulation with a coding rate of 0,5). In addition, while IEEE 802.11a works at frequencies between [5150 - 5730] MHz, IEEE 802.11p uses the ITS band [5855 - 5925] MHz.

The newer version of this standard, IEEE 802.bd, has as main goals to define, at least, i) one working mode that achieves twice the MAC throughput of 802.11p with relative velocities up to 500 kmph, ii) one mode that achieves twice the communication range of 802.11p, and iii) one mode that is compatible with 802.11p devices. Overall, it is expected that the spectrum efficiency and coverage of 802.11bd will be similar to the physical layer of LTE-PC5 Mode-4 [5]. In any case, the MAC operation of IEEE 802.11bd has been continually based on the well known CSMA/CA mechanism for backwards compatibility purposes, and works as follows. Before initiating a transmission, a station senses the channel to determine whether it is busy. If the medium is sensed idle during a period of time called the Arbitrary Inter-frame Space (AIFS), the station is allowed to transmit. If the medium is sensed busy, the transmission is delayed until the channel is idle again. In this case, a slotted binary exponential backoff interval is uniformly chosen in [0, CW - 1], where CW is the contention window. The backoff timer is decreased as long as the channel is sensed idle, paused when a transmission is in progress, and resumed when the channel is sensed idle again for more than the AIFS. When the backoff timer expires, the station attempts transmission. After each unicast data frame successfully received, the receiver transmits an acknowledgment (ACK) frame after a Short Inter-frame Space (SIFS) period. In case the frame is transmitted in multicast or broadcast mode, as it happens in the transmission of Cooperative Awareness Messages, the ACK is not transmitted. The value of CW is set to its minimum value, *CWmin*, in the first transmission attempt and after each successful transmission; and increases in integer powers of 2 at each retransmission, up to a pre-determined value *CWmax*.

B. LTE-PC5

Figure 1 illustrates the resource grid structure of the LTE-PC5 interface used to allow direct vehicle to vehicle communications. In the time domain, the resource grid is divided into subframes of 1 ms. In the frequency domain, a subframe is divided into physical Resource Blocks (RBs) that span 180 kHz. The number of RBs per subframe depends on the available channel bandwidth, with 50 RBs used in a 10 MHz carrier. QPSK and 16QAM modulation schemes are supported for data transmissions.

LTE-PC5 groups RBs in the same subframe into subchannels, and allows to allocate resources with a subchannel granularity. A subchannel is composed of control information and user data. The control portion occupies 2 RBs and is known as the Sidelink Control Information (SCI). The group of RBs carrying user data in a subchannel is known as a Transport Block (TB) and occupies a variable number of RBs depending on the message size. In this paper we assume that the SCI and the TB are configured to be adjacent in the resource grid and that 5 RBs per subchannel are used, resulting in 10 subchannels per subframe in a 10 MHz carrier. Other configurations are possible, and its choice is relevant for the system's efficiency [11].

LTE-PC5 provides two mechanisms to implement resource allocation, namely Mode-3 and Mode-4. In Mode-3 vehicles are assumed to be under the coverage of an eNB (evolved NodeB), and it is the eNB who allocates the resources that are used in the sidelink or PC5 interface. In

Mode-4 vehicles use the Sensing-based Semi-Persistent Scheduling (SPS) distributed channel access mechanism to decide on the resource allocation. Its main idea is to proactively avoid collisions by sensing the channel during a time window.

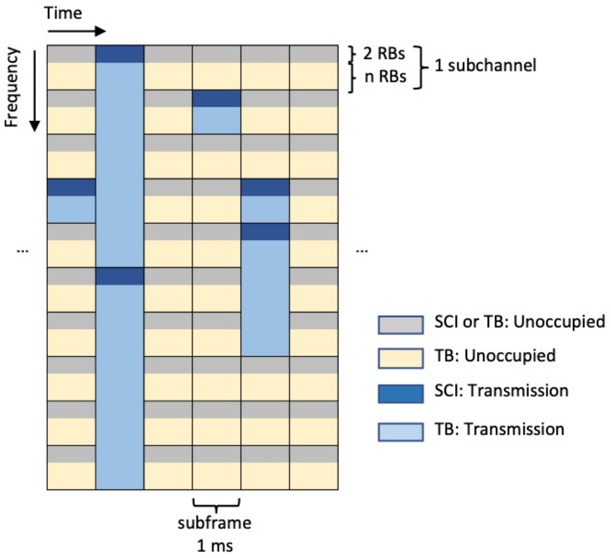

Fig. 1. Structure of the LTE-PC5 resource grid with 10 subchannels per subframe.

A sensing window of typically 1000 ms is considered, where the User Equipment (UE) decodes the received SCIs, and keeps track of the Sidelink Received Signal Strength Indicator (S-RSSI) in each subchannel. When a transmission is requested, a set of potential candidate subchannels is considered within a resource selection window, which has a maximum of 100 ms to limit channel access delay. For each candidate subchannel in the resource selection window, a corresponding set of subchannels in the sensing window is established assuming a periodicity of 100 ms. Consequently, the set of candidate subchannels is pruned removing all the subchannels whose corresponding set in the sensing window was not monitored, or was received with an average S-RSSI exceeding a preconfigured power threshold, which indicates that this subchannel is occupied by another transmitter. If after the pruning process less than 20% of the subchannels in the resource selection window remain, the power threshold is increased by 3 dB and the process is repeated. Finally, the UE selects the subchannel to be used with a random uniform distribution among the best 20% subchannels, in terms of lowest average S-RSSI, remaining in the resource selection window.

The selected resource is maintained for a number of consecutive packet transmissions known as the Resource Counter (RC), which is randomly selected between (*RCmin*, *RCmax*). The RC is decremented by one on each packet transmission. Finally, when the RC goes to zero a keep probability, p_{keep} = (0, 0.8), is used to determine if a new resource selection needs to be triggered. Previous studies have shown that p_{keep} has a small impact on the performance of the SPS algorithm [12].

In the rest of the paper, we assume the following configuration of the SPS algorithm: initial pre-configured power threshold of 95 dBm, p_{keep} = 0.8, and (*RCmin*, *RCmax*) = (5, 15), according to the application generation rate of the CA service.

III. THE COOPERATIVE AWARENESS SERVICE

The Cooperative Awareness Basic Service has been standardized by the ETSI in Europe [13]. A similar service is provided by WAVE in the US using the Basic Messaging Service (BSM). Without loss of generality, we restrict our description in this paper to the European service.

The goal of the CA service is to allow vehicles to maintain awareness of other vehicles in proximity. This is achieved by means of CAM messages that are transmitted periodically, and contain information such as time, position, and motion state of the vehicle. In the broader setting of connected and autonomous vehicles, the CA service can be understood as an extended sensor that allows to track the real-time position of neighboring vehicles. The CA service is a critical ITS facility because safety applications can be built that rely on this service. For example, a collision warning application or a cooperative manoeuvring application can be developed relying on the real-time information about neighboring vehicles provided by the CA service.

The default transmission interval of the CAM message is 0.1 seconds but this interval can be increased up to 1 second depending on the channel congestion status using the Decentralized Congestion Control (DCC) mechanism that operates on top of the MAC layer. In the present paper, DCC has not been explicitly considered as we focus on comparing MAC algorithms of IEEE 802.11p and LTE-PC5 Mode-4 without the interference of any other layer. However, a representative set of CAM intervals is considered in Section 4 to model the effect of DCC. A detailed study of the behaviour of DCC can be found in [14].

After a CAM is authenticated, the receiving vehicle updates a local database known as Local Dynamic Map (LDM) to record the position of the car that transmitted the CAM. In our implementation we assume that an entry in the LDM is erased after 2 seconds without receiving any CAM from the corresponding vehicle.

A. Benchmarking the CAM service: NAR and Position Error

To understand the performance of the CA service we propose two application layer metrics that capture the efficiency and the accuracy of the CA service in the layer in which its information is really used.

The Neighborhood Awareness Ratio (NAR(r)), first introduced in [8], describes the portion of cars registered in a given vehicle's LDM from all the cars that are present at a given radius r from that vehicle. Thus, in a system with N vehicles we can define the system wide NAR at distance r as:

$$NAR(r) = \frac{1}{N}\sum_{i \in N} \frac{|LDM(i)_r|}{|S(i,r)|} \quad (1)$$

, where $LDM(i)_r$ is the number of LDM entries in vehicle i located at a distance below r from vehicle i, and $|S(i,r)|$ is a function that counts all vehicles within distance r of vehicle i. Thus, the NAR metric captures the efficiency of the CA service in terms of the probability of missing neighboring cars. This metric is critical for the CA service because missing neighboring cars affects the performance of safety applications relying on this service.

Another critical metric for the performance of the applications using the CA service is to understand how reliable are the entries of LDM database in a given vehicle. Notice that having an entry in the LDM database does not guarantee that the actual position of the represented vehicle corresponds to the one recorded in the LDM, since neighboring cars move between CAM updates. Thus, we can define an average Position Error (PE) from the perspective of a given vehicle *i* applied to its neighbours inside a radius *r* as:

$$PE(i,r) = \frac{1}{|LDM(i)_r|}\sum_{j\in LDM(i)_r}\sqrt{|LDM(i,j)-pos(j)|^2} \quad (2)$$

, where *LDM(i,j)* represents the stored coordinates of vehicle *j* in the LDM of vehicle *i*, and *pos(j)* represents the coordinates of the actual position of vehicle *j* in the scenario. Hence, we can define the average PE from the system perspective as:

$$PE^{avg}(r) = \frac{1}{N}\sum_{i\in N} PE(i,r) \quad (3)$$

Notice that while NAR captures the efficiency of the CAM service, the PE captures the accuracy of the service.

IV. PERFORMANCE EVALUATION

A. Simulation models and scenarios

In this section we use packet level simulations to analyse the impact of 802.11p and LTE-PC5 at the application level of the ETSI CA service based on the NAR and PE_{avg} metrics introduced in the previous section. For 802.11p we extended the Veins simulation platform, which uses 802.11p models available in OMNeT++ and the SUMO traffic simulator following a Krauss vehicle mobility model [15], to include the two new metrics. To model LTE-PC5 Mode-4 we also departed from the Inet module of OMNeT++ and developed a detailed implementation of the LTE-PC5 frame structure and of the SPS algorithm described in Section 2.

Following the rationale provided in Section 2 we calibrated the physical layers of the 802.11p and LTE-PC5 models to deliver similar coverage ranges and PRR curves when operating with a 10 MHz carrier at 5.9 GHz, transmission power of 200 mW, propagation factor of 3, Rayleigh fading and background noise of -110dBm.

The considered CAM messages have a size of 185 bytes including GeoNetworking and Basic Transport protocols, which translate into an airtime of 344 microseconds in 802.11p using the default data rate of 6 Mbps implemented with a QPSK modulation and 0,5 coding rate, and span 3 subchannels in LTE-PC5, being our configuration 5 RBs per subchannel, MCS index of 7 with QPSK modulation. Additionally, 802.11p is configured with AIFS of 110 microseconds and a CW_{min} of 15. LTE-PC5 does not use HARQ retransmission.

Our goal is to understand the impact of the LTE-PC5 Mode-4 and 802.11p MAC layers on application-level metrics. It is thus essential to analyse both technologies under varying road congestion and vehicle mobility. For this purpose, we define two basic scenarios: i) Fast Highway scenario, representing 1 km highway with 8 lanes (4 lanes on each direction), where on average we have approximately 320 vehicles moving at 100 kmph (1 car every 25 meters, in each lane), and ii) Slow Highway with the same properties, where on average we have 700 vehicles moving at 10 kmph (1 car every 11.4 meters, in each lane). The mobility models in SUMO impose larger inter-car distances when driving faster.

In addition to vehicle speed and density, the other key factor impacting CA service is the CAM interval, which we set to 0.1 seconds, 0.2 seconds and 1 second. These CAM interval values are selected to reflect the minimum interval that keeps the authentication workload bounded (c.f. Section 3), as well as representative intervals allowed by DCC. Note that analysing 802.11p and LTE-PC5 under a set of fixed CAM interval allows to extrapolate the behaviour under a DCC controlled CAM interval.

This section is structured as follows. First, we look at PRR over distance under different CAM interval settings. These results allow us to lay the necessary foundation to understand the behaviour of the application layer KPIs. Subsequently, we evaluate the CA service investigating NAR and PE metrics introduced in Section 3 while looking separately at the Fast Highway and Slow Highway scenarios, and at the impact of the CAM interval.

All metrics reported are obtained averaging the results of multiple simulation runs over distance buckets defined as the distance between transmitter and receiver [16-17].

B. Packet Reception Ratio (PRR)

Figure 2 reports the PRR over distance for the LTE-PC5 Mode-4 (blue solid lines) and 802.11p (red dashed lines) technologies in the Slow Highway scenario for a varying CAM interval of 0.1 seconds, 0.2 seconds and 1 second. We choose the Slow Highway scenario because higher levels of network congestion are attained. Looking at the case when CAM interval is 1 second, we can see that both technologies deliver a similar PRR, since their PHY layers have been calibrated to have the same coverage range and channel congestion is light. In this case, all error transmissions are due to propagation loses. Decreasing the CAM interval to 0.2 seconds and 0.1 seconds, increases channel congestion and results in an increasing gain of LTE-PC5 Mode-4 over 802.11p. The reason for the increased performance of LTE-PC5 Mode-4 lies in the design of the SPS algorithm, which, unlike CSMA/CA, is guaranteed to avoid collisions when there is enough capacity and vehicles can sense each other, and can even deliver a better performance in the case of hidden nodes, if within the last sensing window (1000 milliseconds) two hidden nodes happened to be in coverage of each other.

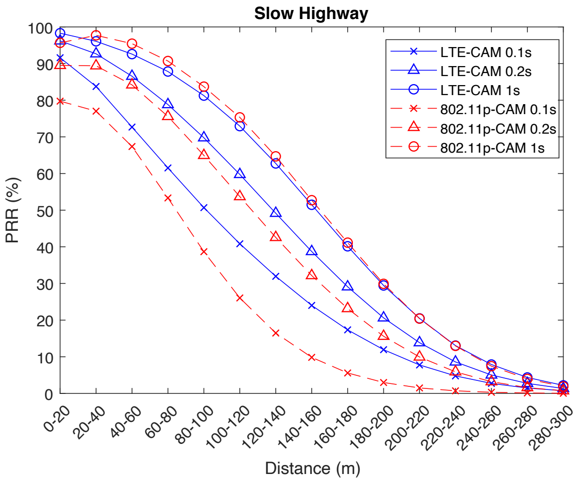

Fig. 2. PRR over distance with a varying CAM interval for LTE-PC5 Mode-4 (blue solid lines) and 802.11p (red dashed lines).

C. *Increasing vehicle density: Fast and Slow Highway*

Figures 3 and 4 depict respectively the results of NAR and Position Error metrics for LTE-PC5 Mode-4 and 802.11p when comparing the Fast Highway and Slow Highway scenarios, using the default CAM interval of 0.1 seconds.

Looking at Figure 3 we can see how the NAR is significantly better than the PRR. The reason is that the application layer of the CA service declares a vehicle as lost after not hearing a CAM for 2 seconds, which allows the service to recover from sporadic CAM reception losses. LTE-PC5 Mode-4 outperforms 802.11p in both scenarios, although the gain is significantly higher in the Slow Highway scenario, given that congestion is higher in this case. In this scenario neighbours are reliable tracked (NAR > 90%) up to 200 meters in LTE-PC5 Mode-4, and up to 160 meters in 802.11p.

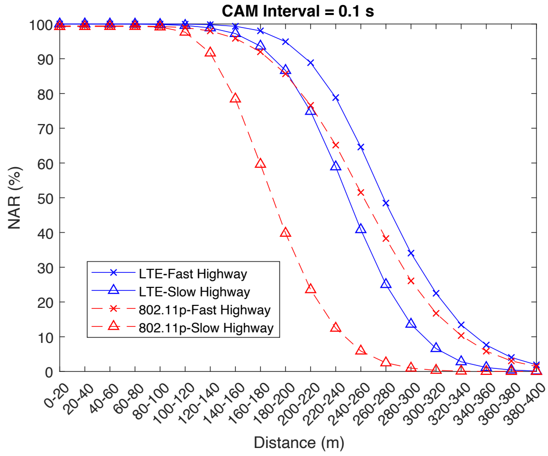

Fig. 3. NAR for LTE-PC5 Mode-4 and 802.11p in Fast and Slow Highway scenarios.

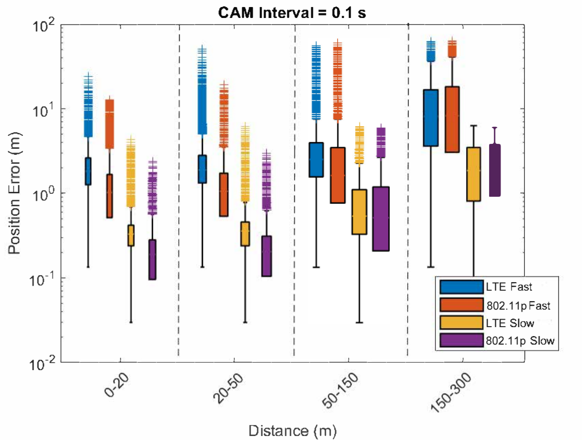

Fig. 4. Position Error for LTE-PC5 Mode-4 and 802.11p in Fast and Slow Highway scenarios.

Figure 4 depicts the PE of the CA service, namely the error between the recorded position of a vehicle in the LDM versus the actual position of this vehicle. Boxplots are used to depict this metric with the box and whiskers representing respectively the 25-75 and the 5-95 percentiles of the distribution, and the crosses representing outliers. Unlike NAR, we can see in this metric that the Fast Highway scenario results in higher errors than the Slow Highway, which is as expected because vehicles move faster and traverse more distance between successive CAM updates. It is also worth noting that, in this case, 802.11p results in slightly lower errors than LTE-PC5 Mode-4, being the reason that 802.11p packets are sent immediately if the channel is empty whereas LTE-PC5 Mode-4 may introduce a delay of up to 100 ms due to the SPS resource selection window. However, lower errors of 802.11p translate only in a moderate advantage in practice. For example, for vehicles located between 0-20 meters in the Fast Highway scenario, LTE-PC5 Mode-4 results in median and worst-case errors of 2 and 11 meters, and 802.11p of 1 and 10 meters. Worst case errors are caused by consecutive CAM losses due to collisions or channel errors. Despite being infrequent, these worst-case errors deserve further study as they may result in dangerous situations on the road. Moreover, in the presented results we assume that vehicles use ideal positioning, but real applications will have to cope with additional position errors introduced by localization systems whose precision ranges from several centimetres to several meters.

Figure 5 displays an interesting interaction between the NAR metric and the CAM interval. Using a longer CAM interval reduces congestion, and hence results in a higher PRR (c.f. Fig. 3). However, having a fixed memory of 2 seconds, the NAR metric has less chances to recover from a packet loss if a longer CAM interval is used. The previous trade-off results in LTE-PC5 Mode-4 having the best NAR performance with a CAM interval of 0.1 seconds, followed closely by the 0.2 seconds one. However, at distances larger than 120m, 802.11p suffers from severe levels of loses when using CAM intervals of 0.1 seconds and this results in a much better NAR performance with a CAM interval of 0.2 seconds for these distances, although being in both cases inferior to LTE-PC5 Mode-4. Using a CAM interval of 1 second results in both cases in a very low NAR, despite being the setting that delivered the highest PRR, since only 2 CAMs are sent before erasing an entry in the LDM. These results illustrate the importance of optimizing MAC settings looking at application layer performance, and not only at MAC metrics. Comparing the NAR results with the PRR ones depicted in Figure 3, we can see that for CAM intervals of 0.1 and 0.2 seconds, the gain of LTE-PC5 Mode-4 over 802.11p is higher when looking at NAR than when looking at PRR, i.e.

$$\frac{NAR_{LTE-PC5}}{NAR_{802.11P}} > \frac{PRR_{LTE-PC5}}{PRR_{802.11P}} \qquad (2)$$

which demonstrates how the application layer design can help amplify the benefits of a more robust MAC layer.

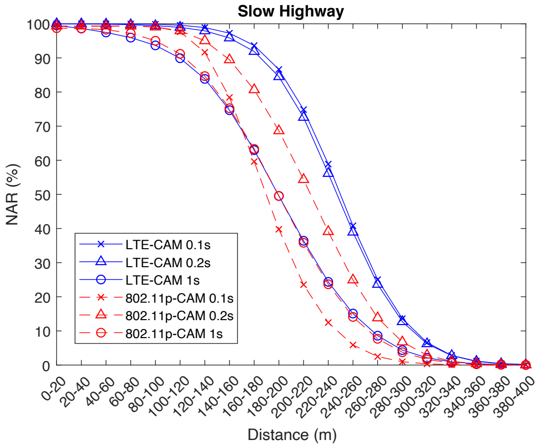

Fig. 5. NAR for LTE-PC5 Mode-4 and 802.11p with varying CAM interval.

Figure 6 depicts the obtained PE in this experiment. Again, we see that at small distances, 802.11p results in slightly lower errors than LTE-PC5 Mode-4, due to its shorter channel access delay. As expected, PE increases for both technologies with the CAM interval for neighboring vehicles below 50 meters, but this dependence becomes less clear as distance increases, since far away vehicles are subject to higher losses. A CAM interval of 0.1 seconds is the setting delivering the smallest PE for both technologies but, in the case of 802.11p, a CAM interval of 0.2 seconds becomes slightly better for far away vehicles due to the high losses, because of congestion when a CAM interval of 0.1 seconds is used. A worst-case PE of 6 meters is obtained in this experiment, since vehicles move at 3 m/s and an LDM memory of 2 seconds is used. These worst-case errors may be very dangerous when considering vehicles in proximity (0-20 meters bucket).

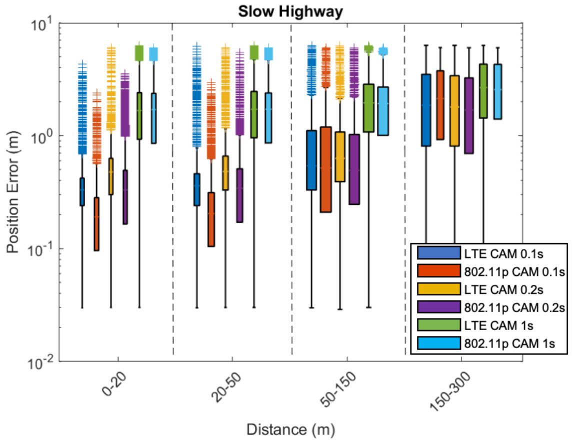

Fig. 6. Position Error for LTE-PC5 Mode-4 and 802.11p with varying CAM interval.

V. CONCLUSIONS

There is a current debate among regulators about the appropriate technology to support future ITS safety services in the 5.9 GHz band. Among these services, Cooperative Awareness, which delivers the position of surrounding vehicles in real time, is of special interest to build the first safety applications such as anticipated collision avoidance or cooperative manoeuvring.

The two commercially ready candidate technologies to support ITS safety services are 802.11p, promoted by the IEEE, and LTE-PC5 Mode-4, promoted by the 3GPP. Although 802.11p enjoys a well-established ecosystem, it is based on an older PHY layer technology. On the other hand, LTE-PC5 Mode-4 has a superior PHY performance but a not so mature ecosystem. Nevertheless, IEEE is currently developing the standard 802.11bd whose backwards compatible enhancements are expected to bring the PHY layer performance on-par with LTE-PC5. It is therefore of interest to understand, once PHY layers will perform similar, the impact that the MAC layer mechanisms of both technologies have on ITS safety services like cooperative awareness.

This paper provides an in-depth simulative study addressing the previous question, while benchmarking the CA service with two application-level metrics: NAR and PE. Our study concludes that, even with equivalent PHY performance, the MAC layer of LTE-PC5 Mode-4 outperforms the MAC layer of 802.11p (or its enhanced version 802.11bd) when road congestion increases, which translates into an improved range to reliably track surrounding vehicles. However, 802.11p/bd results in slightly better vehicle positioning accuracy at lower distances, although for both technologies additional work is needed to limit worst case vehicle positioning accuracy, which can be as high as 11 meters when moving at 100 kmph for vehicles at 0-20 meters distance.

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