3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications?

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***Abstract*—The concept of vehicular ad-hoc networks enables the design of emergent automotive safety applications, which are based on the awareness among vehicles. Recently, a suite of 802.11p/WAVE protocols aimed at supporting car-to-car communications was approved by IEEE. Existing cellular infrastructure and, above all 3GPP LTE, is being considered as another communication technology appropriate for vehicular applications. This letter provides a theoretical framework which compares the basic patterns of both the technologies in the context of safety-of-life vehicular scenarios. We present mathematical models for the evaluation of the considered protocols in terms of successful beacon delivery probability.**

***Index Terms*—Automotive safety, cooperative awareness, beaconing, hybrid vehicular networks, VANETs, 3GPP LTE, IEEE 802.11p/WAVE.**

I. INTRODUCTION

COLLISION avoidance, lane change warning, electronic brake and many other next generation *cooperative active safety* applications, which help to increase the ”horizon of awareness” for the driver, rely on the assumption that vehicles are able *to communicate* with each other and with infrastructure [1]. Recently, a suite of 802.11p/1609 Wireless Access in Vehicular Environments (WAVE) protocols aimed at supporting car-to-car communications was approved by IEEE. However, both the potentials of WAVE technology in particular, and socio-economic challenges of Vehicular Ad hoc NETworks (VANETs) concept in general are currently being widely discussed in governmental, standardization, industrial and academic communities [2].

One of the key drawbacks of the IEEE 802.11p is its low *scalability* which lies in the fact that the protocol is unable to provide the required time-probabilistic characteristics in dense road scenarios, i.e. when the number of cars in the same area is high [3], [4]. In addition, VANETs are based on primarily direct car-to-car communications and, therefore, are subject to ”network effect”, which leads to the problem of a proper deployment strategy design.

The above motivates consideration of the potential of *existing* cellular broadband wireless infrastructure and, particularly 3GPP LTE, as a communication basis for vehicular cooperative safety systems. Such kind of study with respect to UMTS is performed in [5]. Whether or not LTE is an appropriate technology for critical car applications is an urgent open question which has been recently discussed, e.g., during the specialized panel at [6]. Currently, few studies exist which have addressed this question. In [7] and [8] the mean vehicle-to-vehicle delays for different scenarios are obtained by means of *simulations* of LTE networks. The results presented in the above studies are somewhat contradictory. For example, [7] shows that when transmissions of periodic cooperative awareness messages are performed by LTE, the capacity of the network is limited by the downlink data channel. In turn, [8] argues that the uplink data channel is a bottleneck of the LTE network for the intelligent transport systems use cases. Differences between the conclusions from [7] and [8] are mostly due to the *different assumptions* used by the authors in their simulation studies.

This letter is the first to provide an *analytical* framework which allows comparing 802.11p/WAVE and LTE protocols in terms of the probability to deliver the beacon before the expiration of the deadline. Our goal is analyze the abilities of these protocols to provide cooperative vehicular awareness. The approach presented is simple and provides insights into the theoretical limitations of the two considered technologies.

The letter is organized as follows. Section II presents stochastic models for the evaluation of the 802.11p/WAVE and LTE and Section III presents the numerical results and conclusions.

II. SYSTEM MODEL

A. Basic Principles

Cooperative safety applications are based on the frequent exchange of short status messages also known as *beacons* by the vehicles. Beacons carry the information about the vehicle, such as its position, velocity and acceleration.

In VANETs, which are based on 802.11p, beacons are *broadcast* periodically by each vehicle. Communication range is normally in the order of several hundred meters and, therefore, beaconing provides awareness about the vehicles in the vicinity (Figure 1). Carrier Sense Multiple Access (CSMA) *distributed* medium access control scheme is adopted in 802.11p. Therefore, beacons are subject to collisions in the wireless channel.

In the infrastructure-based *centralized* LTE approach, beaconing can be implemented as follows. All the vehicles in the cell transmit in the uplink channel their beacons to the base station (eNodeB). Then, the beacons reach the Mobility Management Entity (MME) or the Serving Gateway (SGW), which are the components of the Evolved Packet Core, and come back to the base station. After this, the base station transmits the beacons which are relevant to each vehicle in the

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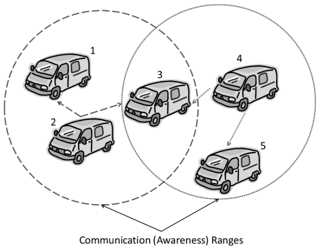

Fig. 1. Beaconing in IEEE 802.11p/WAVE.

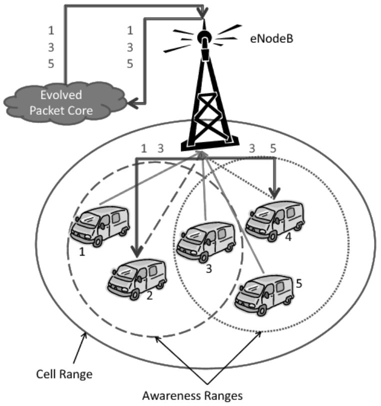

Fig. 2. Beaconing in 3GPP LTE.

downlink channel (Figure 2)[1]. In practice beacons will coexist with other types of traffic which are transmitted in cellular network and, therefore, proper scheduling at the base station is vital for achieving the required beaconing performance.

In this letter we derive the probabilities of delivering the beacon before the expiration of its deadline for 802.11p/WAVE and LTE networks. The deadline is assumed to be equal to the beaconing period. In other words, the beacon is considered to be outdated and is dropped, if it is not transmitted to the intended recipients, when the new one arrives[2].

B. IEEE 802.11p/WAVE

WAVE adopts an alternating access scheme: the channel is divided into the Synchronization Intervals of a fixed length, which consist of an equal length control channel (CCH) and service channel (SCH) intervals started by the guard times of length T_g (Figure 3). Beacons are transmitted in the CCH interval, the duration of which is denoted as T_{CCH}. A vehicular node calculates the *backoff* delay measured in the number of aSlotTime (σ) values. The backoff counter is a random variable, uniformly chosen from a range of integer numbers determined by Contention Window (W). A node decreases the counter every aSlotTime if it detects the channel idle for an Arbitrary InterFrame Space (AIFS) after the successful transmission event[3]. As soon as the counter turns to zero, the node is allowed to access the channel. Beacons are never acknowledged by the receivers.

This letter makes the following simplifying assumptions about WAVE [4]:

- there are N nodes within the reciprocal communication range, i.e. there are no hidden terminals;
- the communication range coincides with the carrier sense range and the awareness range.

The radio channel is assumed to be in one of the following possible states[4]: idle, success, or collision. If all beacons are generated at the beginning of the Synchronization Intervals, then the mathematical approach from [4] can be applied and the following recursive relationships are valid:

$$\begin{aligned} X_{WAVE}(t,w,n) &= P_0(w,n)X_{WAVE}(t-\sigma,w-1,n) + \\ &+P_1(w,n)[1+X_{WAVE}(t-T_s,w-1,n-1)] + \\ &+\sum_{k=2}^{n} P_k(w,n)X_{WAVE}(t-T_c,w-1,n-k), \end{aligned}$$

where $X_{WAVE}(t,w,n)$ is the mean number of successful beacon transmissions during the CCH interval of duration t given that, at most, w contention slots are left at the vehicles' counters and n vehicles have not attempted to transmit yet. Other notations are as follows:

$$P_i(w,n) = \binom{n}{i}(\frac{1}{w})^i(1-\frac{1}{w})^{n-i},$$

$T_s = T_h + L/R + AIFS$ and $T_c = T_h + L/R + EIFS$, where L is beacon size and T_h is duration of the physical layer convergence protocol preamble and header. Finally, the target probability of beacon delivery is

$$P_{WAVE} = X_{WAVE}(T_{CCH} - T_g - L/R, W, N)/N.$$

C. 3GPP LTE

LTE Frame is composed of 10 Subframes of length x. Each Subframe is dedicated to the uplink (UL) transmission, downlink (DL) transmission or represents a special (S) Subframe (Figure 4). Special Subframe includes DwPTS (Downlink Pilot Timeslot) of duration d, GP (Guard Period) of duration g, and UpPTS (Uplink Pilot Timeslot) of duration u. Seven uplink/downlink *configurations* are specified, which assign a particular type to each Subframe.

The following simplifying assumptions about LTE are made in this letter:

- there are N_{CELL} vehicles in the cell and $N-1$ vehicles within the awareness range of an arbitrary vehicle[5];
- round-trip eNodeB-MMS/SGW beacon delay is ignored;
- management overhead and background traffic are not considered, so all the network capacity is used exclusively for the transmissions of beacons.

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[1] To implement beaconing in this way, all the beacons are to be sent to the backend system, where a special application determines the relevant receivers for each beacon based on the vehicle's geographical information [7].

[2] This metric is similar to the mean beacon car-to-car delivery delay which is used in [7] and [8]. According to our definition, the beaconing delay cannot exceed the beaconing period. Beacons which experience larger delays contribute to a decrease in delivery probability.

[3] Extended (EIFS) is used instead of AIFS whenever the physical layer indicates an unsuccessful transmission event.

[4] Throughout this letter we assume that the radio channel is ideal, so bit errors are ignored.

[5] $N-1$ has the same physical interpretation both in WAVE and LTE models and represents the number of nodes in the awareness range of an arbitrary vehicle, i.e. the range covering the nodes whose beacons should be delivered to this vehicle due to the requirements of safety applications.

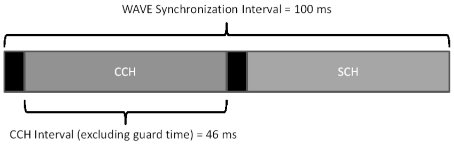

Fig. 3. Basic temporal relationships in IEEE 802.11p/WAVE.

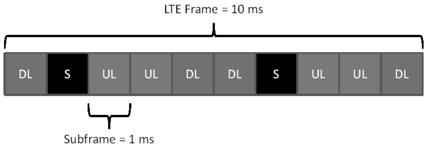

Fig. 4. Basic temporal relationships in 3GPP LTE.

Let us consider a *sequence* of Subframes during the beaconing period starting from the first UL Subframe and ending with the last DL Subframe. Let there be y *continuous intervals* of UL Subframes or DL Subframes in this sequence[6]. The number of beacons which can be transmitted during the i-th sequence of UL Subframes is $U(i) = \lfloor \frac{u+Y_i^{UL}x}{L/R_U} \rfloor$, whereas the analogous value for DL subframes is $D(i) = \lfloor \frac{Y_i^{DL}x+d}{L/R_D} \rfloor$, where i is integer out of the range $1 \dots y$. Notations are as follows: Y_i^{UL} and Y_i^{DL} is the numbers of subframes in the i-th continuous interval for UL and DL, R_U and R_D are uplink and downlink data rates and L, as before, is beacon size. The following recursive relationships are valid for the beaconing:

$$\begin{aligned}
A(1) = \min(U(1), N_{CELL}), A(i) = \min(U(i), \bar{A}(i-1)),\\
\bar{A}(1) = N_{CELL} - A(1), \bar{A}(i) = \bar{A}(i-1) - A(i),\\
B(1) = \min(D(1), A(1)N),\\
B(i) = \min(D(i), \bar{B}(i-1) + A(i)N),\\
\bar{B}(1) = A(1)N - B(1), \bar{B}(i) = \bar{B}(i-1) + A(i)N - B(i),
\end{aligned}$$

where $A(i)$ is the number of vehicles which transmitted in the i-th sequence of UL Subframes, $\bar{A}(i)$ is the number of vehicles which has not yet transmitted by the end of this sequence, whilst $B(i)$ is the number of beacons transmitted in the i-th sequence of DL Subframes and $\bar{B}(i)$ is the number of beacons which have not yet been transmitted by the base station in the downlink by the end of this sequence. Finally, the target probability of beacon delivery is

$$P_{LTE} = 1 - (\bar{A}(y)N + \bar{B}(y))/(N_{CELL}N).$$

III. NUMERICAL RESULTS AND CONCLUSIONS

We conducted a series of experiments with the developed analytical models and the corresponding simulators for the typical beaconing parameters presented in Table I. In our settings a vehicle generates a beacon once per one WAVE Synchronization Interval or per ten LTE Frames. The main parameters used for the 802.11p/WAVE and LTE modeling are taken from [4], [9] and are summarized in Tables II and III respectively.

TABLE I
BEACONING PARAMETERS

Parameter	Value
Beaconing rate	10 Hz
Beacon size (L)	300 bytes
Beacon delivery deadline	100 ms

TABLE II
MAIN IEEE 802.11P/WAVE PARAMETERS

Parameter	Value
aSlotTime (σ)	16 μs
AIFS	64 μs
EIFS	188 μs
Header duration (T_h)	40 μs
Data rate (R)	3 Mbit/s
Synchronization Interval duration	100 ms
CCH interval duration (T_{CCH})	50 ms
Guard time (T_g)	4 ms

Probabilities of beacon delivery before the expiration of its deadline in 802.11p/WAVE P_{WAVE} for a different number of vehicles N and different values of Contention Window W are presented in Figure 5. Two conclusions can be drawn. First, for any W value when $N = 50$, P_{WAVE} never exceeds 0.83, which is lower than required in typical safety applications [1]. Second, enlargement of W helps to increase the reliability of beaconing. However, this solution has a major limitation: for large values of W, beacons are lost not only because of collisions, but also because of expiry of the CCH interval, see [4].

Probabilities of beacon delivery before the expiration of its deadline in LTE P_{LTE} for different number of vehicles in the cell N_{CELL} are presented in Figures 6 and 7. Three strategies of the base station operation are examined. The first strategy is in line with [8] and assumes that the base station simply broadcasts in the downlink all the received beacons to all the vehicles in the cell ($N = 1$, ”downlink broadcast”). The other two strategies are in line with [7], namely, each received beacon is sent to every vehicle in the cell ($N = N_{CELL}$, ”downlink unicast”) or to every vehicle in the corresponding awareness range ($N = 50$, ”downlink unicast with filtering”). It can be concluded that the last two strategies are not appropriate for safety-related applications since the downlink channel becomes overloaded; this also corresponds to the results presented in [7]. Although the ”downlink broadcast” performs better, when downlink/uplink ratio is 9:1, the uplink channel becomes a bottleneck already for $N_{CELL} = 300$.

Regarding the question posed in the title of this letter, we can conclude that the abilities of LTE to support beaconing for vehicular safety applications are poor. The network easily becomes overloaded even under the idealistic assumptions[7]. Moreover, cellular network is not available for this kind of operation at no cost. Therefore, in our opinion the ad-hoc

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[6] For the studied sets of parameters and for any uplink/downlink configuration, the number of UL Subframes is equal to the number of DL Subframes in the considered sequence.

[7] Our model of LTE neglects all the management overheads and ”normal” traffic in a cellular network. The modeling is performed for the peak data rates. Moreover, the round-trip eNodeB-MMS/SGW beacon delay is ignored. According to the experimental studies (e.g. see the materials of the panel at [6]) this delay is in the order of 50 ms. Therefore, the presented dependencies can be treated as the *upper bounds* for the practical values of the beacon delivery probability in LTE.

TABLE III
MAIN 3GPP LTE PARAMETERS

Parameter	Value
Uplink peak data rate (R_U)	50 Mbit/s
Downlink peak data rate (R_D)	100 Mbit/s
Frame duration	10 ms
Subframe duration (x)	1 ms
DwPTS (d)	5/7 ms
UpPTS (u)	1/7 ms
GP (g)	1/7 ms

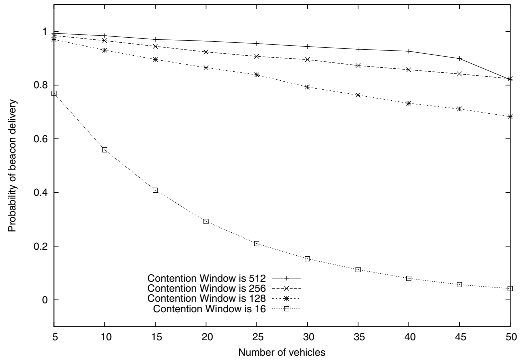

Fig. 5. 802.11p/WAVE beaconing performance.

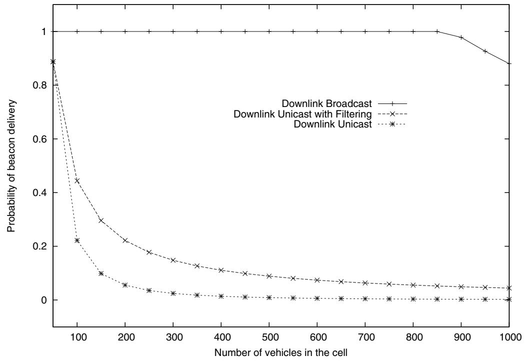

Fig. 6. LTE beaconing performance when downlink/uplink ratio is 3:2.

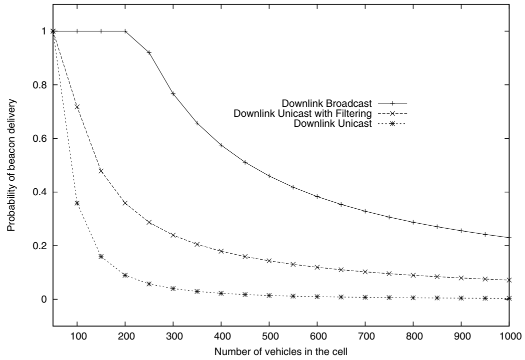

Fig. 7. LTE beaconing performance when downlink/uplink ratio is 9:1.

WAVE architecture looks more promising for vehicular safety. Introduction of dual radio devices, which allow having a dedicated transceiver for exchange of safety information and avoiding channel switching during beaconing, will improve the scalability of 802.11p/WAVE.

Our future work will target the design of more realistic LTE models [10] for the study of the beaconing performance.

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