Modeling and Evaluation of LTE in Intelligent Transportation Systems

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Abstract. The term *Intelligent Transportation Systems* (**ITS**) refers to adding information and communications technology to transport infrastructure and vehicles. The IEEE 802.11p standard is considered the main candidate for communication within the context of ITS and it performs well for active safety use cases thanks to its very low delay. Nonetheless, there are still some problems that originate mostly from the decentralized ad-hoc nature of the protocol, that lead us to believe that the information exchange in ITS can also be handled via a different kind of network. In this paper, the technical feasibility of the use of LTE for ITS communication is examined. A model was built simulating the function of the LTE evolved Radio Access Network (eRAN) operating in a vehicular environment and its performance is evaluated. The results are encouraging and indicate that LTE can be used to handle certain types of traffic in a vehicular network.

Keywords: LTE, ITS, 802.11p, vehicular communications

1 Introduction

The IEEE 802.11p standard [1] is considered to be the future of Vehicular Ad-hoc Networks (VANETs) and is capable of providing vehicle-to-vehicle (V2V) and Infrastructure-to-Vehicle (I2V) communications. The standard will be used for communications within the concept of ITS, and will support safety, traffic efficiency and infotainment applications such as collision avoidance, traffic avoidance, commercial applications and others. The 802.11p is suitable for vehicular communications mainly due to its very low end-to-end delay, which is a crucial factor for ITS applications, especially for the ones which aim at road and vehicle safety and hence, have very stringent timing requirements. A comprehensive list of ITS classes, applications and requirements can be found in [2]. Nonetheless, 802.11p also faces some severe prob-

lems which mainly originate from its decentralized ad-hoc nature, and degrade its performance significantly in some cases. Some of the most important problems are: the hidden node problem, the scalability issues, the degradation of performance under high mobility of the nodes and the use of optimal transmit power by the nodes in order to minimize interference.

These issues, make apparent the need for a search for an alternative communications protocol that will either assist or replace 802.11p for use in ITS. The 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) is an attractive solution mainly due to its extraordinary performance and the fact that it is an infrastructure-based communications system, thus, not facing the same problems as 802.11p. LTE's extraordinary features such as the extremely low end-to-end delay, the high data rates, the large communication range and the fact that it is readily available (commercial networks are already being operational or deployed), make it an ideal candidate for use in ITS networks.

This paper presents the work carried out in [3], in which the performance boundaries of LTE technology in relation to the requirements of typical ITS applications are explored. Moreover, the way that the different parameters of the vehicular network, such as vehicle density and beaconing frequency, affect the performance of LTE is investigated. Furthermore, the effect that the introduction of LTE in ITS has on existing cellular traffic is examined and different possibilities for improving the performance of LTE in the ITS context are investigated.

The remainder of this paper is organized as follows. In section II the model that was used to evaluate the performance of LTE in ITS networks is described, the simulation scenarios are presented and the simulation choices that were made, are motivated. In section III the radio resource management is discussed. The calculation of the users bit rate and the effect of the mobility of the nodes is explained and the transmit power control, retransmission and scheduling schemes are presented. In section IV the simulation results are presented and analyzed while the performance of LTE is evaluated. Finally, in section V we draw our conclusions based on the simulation results.

2 Model Description

Before going any deeper into the details of the model, we have to motivate some of the basic modeling choices that were made. In general, the LTE downlink (DL) path, meaning the communication from the evolved Node B (eNB) to the user equipment (UE) tends to perform better than the uplink (UL) path (UE→eNB), thus offering higher throughput and smaller delays. This is mainly due to the fact that the DL is heavily dependent on the eNB which offers great transmission and computational power. The eNB can use a more advanced Multiple Input Multiple Output (MIMO) scheme, since it has more transmit antennas and can also make use of broadcasting. On the other hand, the UL is heavily dependent on the UE, meaning restricted transmission and computational power, limited battery life and a simpler MIMO scheme for transmission. For these reasons, we consider the UL to be the bottleneck of the

system, especially when used in the highly dynamic vehicular environment, so we chose to focus on modeling the UL in detail. The DL on the other hand was simulated by a simple broadcast scheme, which is reasonable since that is the way that ITS applications operate (one vehicle transmitting to multiple neighboring vehicles).

The function of a LTE network operating in a vehicular environment was simulated by a model created within TNO using the Borland Delphi programming language. The environment that our model simulates and its basic principles are depicted in Figure 1. The vehicles communicate with each other over a commercial LTE network (ITS traffic), at the same time that other mobile users are establishing data connections with the same network (background traffic). The vehicular environment simulated is a rural highway with multiple lanes and a variety of traffic patterns. The LTE part of the model simulates the function of a LTE cell operating in the 900 MHz band with a bandwidth of 10 MHz. The eNB of the cell is situated in the middle (lengthwise) of the simulated highway, at a height of 30 meters and uses an omni-directional antenna. LTE serves both vehicular and background mobile telephony users at the same time and it has to meet the Quality of Service (QoS) requirements for each service, respectively, although in our scenario no QoS is taken into consideration for the background traffic.
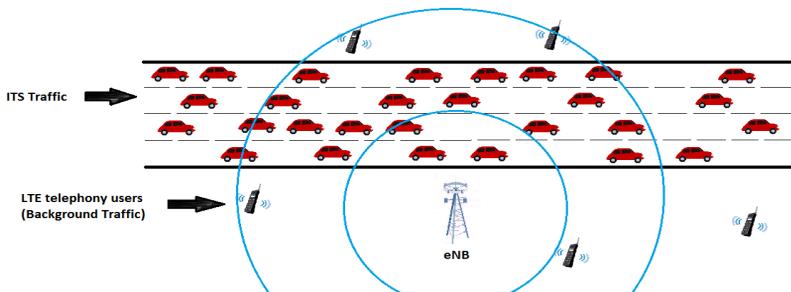

Fig. 1. Basic modeling scenario

In this basic simulation scenario that is presented in Figure 1, all the vehicles participate in an ITS and exchange periodic messages with each other through the eNB. Because these messages have predefined size and are generated at regular intervals, they are called *beacons*, and the frequency with which they are transmitted is called *beaconing frequency*. Each beacon transmitted by each vehicle has to reach the eNB and go through the whole LTE network before it can be delivered to the rest of the ITS users, through a broadcast transmission by the eNB. In our scenario only one cell (eNB) is taken into account, so there is no rebroadcasting from neighboring eNBs.

For the creation of the road network and the simulation of the movement of the vehicles, the Intelligent Driver Model (IDM) developed by Treiber, Hennecke and Helbing was used [4] [5]. In traffic flow modeling, the IDM is a time-continuous car-following model for the simulation of freeway and urban traffic. In our model, the initial positions and velocities of the vehicles were taken from a uniform distribution and they were recalculated with a refresh rate of 100 ms, which ensured that the model adapts well to the changes of the channel. Moreover, the IDM was updated in order

to allow for the creation of multiple lanes (for traffic towards the same direction) and the insertion of traffic jams, in order to simulate realistic traffic patterns.

Every vehicle on the highway transmits a beacon of predefined size with a fixed beaconing frequency. The most common value for the beacon size is 100 Bytes and the most common beaconing frequency is 10 Hz, but the values of these parameters change depending on the ITS application that is served. Here, we will examine only the case of the periodic beacon transmission from the vehicles and not the case of event triggered messages (see[2]).

In our model, each vehicle picks a random initial time to generate its first beacon from a uniform distribution, and after the generation of the first beacon, all the subsequent beacons follow in fixed time intervals depending on the beaconing frequency (a beaconing frequency of 10 Hz leads to a beacon inter-arrival time of 100 ms). Then, the ITS users have to wait for the eNB to assign resources to them depending on the scheduling scheme that is implemented (see Section III), in order to be able to transmit their beacon. The UL transmission delay of the beacon is defined as the elapsed time from the generation of the beacon until the transmission of the last bit of the beacon. For the DL path (eNB→UEs), a broadcast transmission was assumed and the broadcasting bit rate was adapted to the receiver with the weakest signal. So, the vehicle with the lowest bit rate (which is usually the vehicle situated farthest away from the eNB) at any given moment, defines the bit rate of the broadcast transmission and hence the DL transmission delay. The rest of the path that a packet travels through the LTE network was not simulated, but some typical values regarding the delay of the packet were taken into account from [6]. So, a core network delay of 2 ms was used, the processing delay both at the eNB and the UE was set at 4 ms and the buffering delay at the UE was set at 1 ms. The transition delay for the UE between idle and active states, which is usually around 100 ms, was not taken into account since it is assumed that the continuous beacon transmissions will keep the UEs in the connected state. By adding the above mentioned delay components we can calculate the end-to-end delay of each beacon in the system.

The background traffic was modeled as data transmissions from the UEs to the eNB. The arrival of the background data calls followed a Poisson process with average arrival rate λ, and the data call size was randomly sampled from a lognormal distribution with mean M=800 kbits and a coefficient of variation C=1.5. The position of the background call in the cell was selected randomly within the bounds of the LTE cell, and its position did not change throughout the whole transmission (zero mobility assumed for background traffic). Each background data call that arrives in the system enters a buffer (no admission control implemented) and waits there until it is assigned resources from the eNB to start transmitting. When all the data have been sent to the eNB successfully, the entry for the specific data call is erased from the buffer.

As far as the propagation environment is concerned, the shadowing effect and the multipath fading are not modeled, since these propagation effects are dominant in urban environments where there are a lot of reflective surfaces, but for the case of rural environments their effect on the received signal is minimal. Apart from that, the propagation characteristics in our model were calculated as follows. The path-loss of the users in the cell was calculated according to the Okumura-Hata model for rural

areas [7] and from that, the Signal to Interference and Noise Ratio (SINR) per Physical Resource Block (PRB) was calculated according to equation (1):

$$SINR^{PRB} = \frac{P_{Tx}^{PRB}/PL}{I+N} \qquad (1)$$

Where P_{Tx}^{PRB} is the UE transmission power per PRB, PL is the path-loss, I is the interference in Watts and N is the thermal noise in Watts. Since no neighboring cells were modeled to create inter-cell interference, typical values from literature ([8] and [9]) were used, and so the value for interference and thermal noise was set to I = N = -116 dBm.

3   Radio Resource Management

In this section we will discuss how our model allocates the radio resources of LTE (PRBs) to the users of the network. Since the size of the ITS beacons is fixed and known, we have to know the individual bit rate that each user can support at any given moment in order to know and allocate the necessary number of PRBs. In order to do that we used a procedure that models the Adaptive Modulation and Coding scheme (AMC) of LTE, and uses the Shannon bound to calculate the bit rate per PRB for every user. This process is given by equation (2):

$$Bit\ Rate^{PRB} = B^{PRB} \times (\alpha \times \log_2(1 + SINR^{PRB})) \qquad (2)$$

Where B^{PRB} is the band width per PRB (180 kHz) and α is an attenuation factor representing implementation losses. From the literature [7] it was shown that $\alpha=0.4$ is an appropriate value for the modeling of the UL, while $\alpha=0.6$ is appropriate for the modeling of the LTE DL. The effect of the highly dynamic vehicular environment and the way it affects the performance of LTE, was taken into account by adjusting the bit rate of each moving vehicle according to its current velocity. This adaptation of the bit rate to the velocity of the vehicles was done according to the findings of LSTI in [10] and the details of implementation in our model are shown below.

- **User velocity**: 1.39 m/s <= v <= 8.35 m/s → **bit rate reduction**: 4%
- **User velocity**: 8.36 m/s <= v <= 33.3 m/s → **bit rate reduction**: 12%
- **User velocity**: 33.3 m/s < v   → **bit rate reduction**: 15%

The transmission power used by each user in the LTE network is dictated by the Transmit Power Control (TPC). To avoid the complexity of TPC we chose to implement an open loop power control scheme in our model. In a LTE network, the eNB broadcasts the optimal target received power level per PRB and the UEs choose correspondingly their transmission power levels according to their path loss and the number of PRBs allocated to them at the time. In our model, we assume the users are always aware of the target received power level of the eNB, thus enabling them to calculate their optimal transmission power level in order for their transmission to reach the eNB. The received power level per PRB at the eNB was set at P_0 = -78 dBm, based on [8], [9] and [11]. Additionally, we assumed that all vehicles are equipped with the highest class terminals that are defined by the LTE standard. That means that the maximum transmission power of a vehicle is P_{UE_MAX} = 23 dBm, which puts an upper bound to the number of PRBs that can be allocated to the users.

In order to make our model more accurate and realistic a retransmission scheme was implemented to simulate the block error rate of the network. In LTE, packets are retransmitted in case of loss, which affects the transmission time and the available resources significantly. A literature research in [12], [13] and [2] indicated that a retransmission ratio (or packet loss) of 1% for the ITS traffic and 10% for the background traffic was very realistic according to the specifications of the two applications. In our model each time that a retransmission occurs, a retransmission penalty of 8 ms is added to the end-to-end delay of the beacon and the necessary resources for the retransmission are reserved.

As far as resource scheduling is concerned, we chose to implement three different scheduling schemes, dynamic scheduling (fair sharing), dynamic scheduling (priority for ITS traffic) and Semi-Persistent Scheduling (SPS) for ITS traffic/dynamic scheduling for background traffic. When dynamic scheduling is used the eNB makes scheduling decisions and assigns PRBs to the users on demand, every Transmission Time Interval (TTI) which has a duration of 1 millisecond. This process involves a lot of control signaling overhead, since for every beacon, the users have to send requests for resource assignment and the eNB has to signal back to them, with the resource allocation grant. When fair sharing is used, all the users in the network are treated with the same priority, while when priority for ITS traffic is used, the eNB will first serve all the ITS users that have requested resources and if there are remaining resources within this TTI, they will be allocated to the background users.

Semi-Persistent Scheduling (SPS) is a combination of persistent scheduling for initial transmissions and dynamic scheduling for retransmissions. At the beginning of each active period, the UE sends an uplink resource request to the eNB. On receiving the resource request, the eNB allocates a sequence of PRBs located with a certain periodicity between them, where the UE can send all its initial transmissions. When needed, the eNB may reallocate different resources to enable link adaptation. The UE will keep sending its packets using the same PRBs without sending requests or waiting for grants every TTI, until the eNB reallocates the resources of the cell according to the refresh rate of the SPS scheme. In this way a large portion of control signaling is eliminated [13].

The exact gain in resources that is offered by SPS depends on the periodicity and refresh rate that are chosen for the scheme, which in turn depend on the application being served. After some research in [12] and [13] we decided to model our SPS scheme to use 25% of the total control signaling resources that dynamic scheduling is using. The periodicity of the SPS scheme for ITS applications depends on the beaconing frequency of each individual application. The most demanding ITS application have a beaconing frequency of 20 Hz, which means that a SPS periodicity of 50 ms is needed in order to provide resources for the transmission of one beacon every 50 ms. After some testing with our simulator, we came to the conclusion that SPS would operate optimally with a refresh rate of 10 s (persistent allocations are reassigned) and with the assignment of one extra PRB per user in order to accommodate for the highly dynamic vehicular environment which would cause beacons to be dropped because of the outdated PRB allocations.

4   Simulation Results & Analysis

A large number of simulation runs were performed, with different random seeds, in order to ensure statistical accuracy. For all the results that are presented in this paper, the 95% confidence interval is smaller than 4% of the displayed mean value. The values of the main parameters of our model during these simulation runs, are shown in Table I.

Table 1. Simulation parameters values

Parameter	Value	Parameter	Value
Nº of highway lanes	4	Beaconing frequency	10/20 Hz
Road length	2000 m	Beacon size	100 Bytes
LTE Cell radius	1000 m	Average vehicle velocity	30 m/s
Height of eNB	30 m	Velocity fluctuation	6 m/s
No of Background calls	3600	Simulated time	1800 sec
Background call arrival rate	2 calls/sec	Average background call size	800 kbits

As mentioned before, in order for the ITS applications to be able to work over LTE, their beacons have to be delivered within the ITS delay requirements (usually 50 or 100 ms). Figure 2 below depicts the average end-to-end beacon delay experienced by all users in the network for an increasing number of participating vehicles, for two different beaconing frequencies f=10 Hz and f=20 Hz, when dynamic scheduling with fair sharing is used. As we can see, the beacon delay offered by LTE is for

the most part, well below the ITS imposed upper bounds. Under normal load conditions (load below 95%), the beacon delay is around 18 ms and it increases slightly as the load imposed on the network increases.
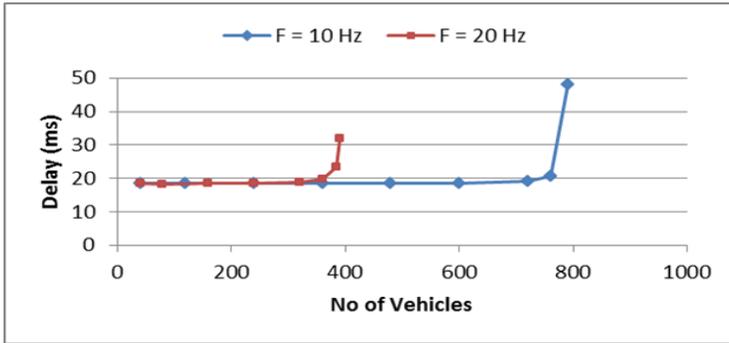

Fig. 2. Average end-to-end beacon delay

Except for the average beacon delay, the cumulative distribution function of the beacon delay for the case of 360 participating vehicles is shown in Figure 3. The figure shows that for both beaconing frequencies, none of the beacons exceeds the most stringent ITS requirement (50 ms) but in the case of f=10 Hz all the beacons are delivered faster due to the decreased load on the network.
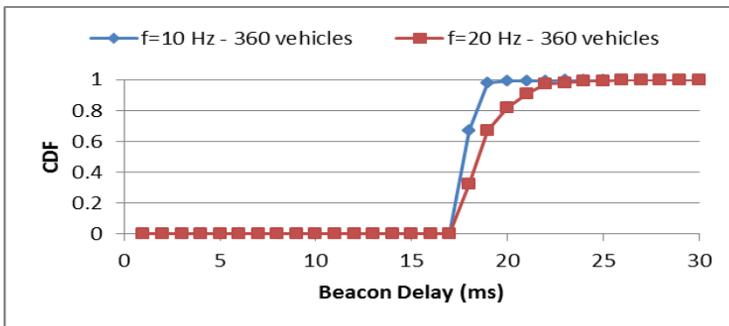

Fig. 3. Cumulative Distribution Function of the end-to-end beacon delay

Another interesting observation is that when the beaconing frequency is doubled the capacity of the LTE network in terms of vehicles that can be served, is almost halved. This is an expected behavior since every vehicle in the network is offering double the load. The fact that none of the beacons experiences a delay lower than 17 ms, even with an unloaded network, is due to the transmission path that every beacon takes through the LTE network. The UL and DL transmission delay, the core network delay, the buffering and processing delay, create this lower limit for the end-to-end beacon delay.
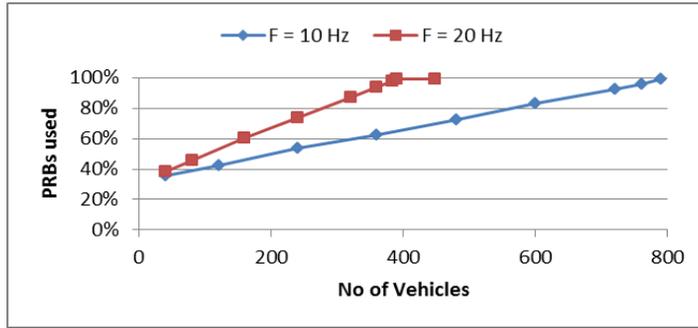
Fig. 4. Total network load vs No of vehicles

Figure 4 shows the percentage of LTE resources (PRBs) used to serve the traffic on the network. As we can see the load increases linearly with the number of vehicles in the network, while the constant background traffic (1.6 Mbps) amounts for about 32% of the load. By comparing this figure with Figure 2 we observe that when the load on the network approaches 100% the beacon delay increases abruptly. The above observations, mean, that LTE can easily serve ITS applications until its capacity limit is reached. As the load of the network gets close to 100%, the performance of LTE degrades abruptly and can no longer serve the ITS applications.

Apart from the performance of ITS applications over LTE we also want to evaluate the effect that the introduction of ITS traffic will have on the existing background LTE traffic. Figure 5 depicts the probability of a background call experiencing throughput below certain thresholds for the case of f=10 Hz and thus giving us an impression about the QoS experienced by the background calls. The figure shows that the throughput of the background calls, drops significantly when the number of vehicles in the network exceeds 600 and the background call QoS is significantly degraded. Even so, a large number of vehicles can be accommodated without having an impact on the performance of the background traffic.
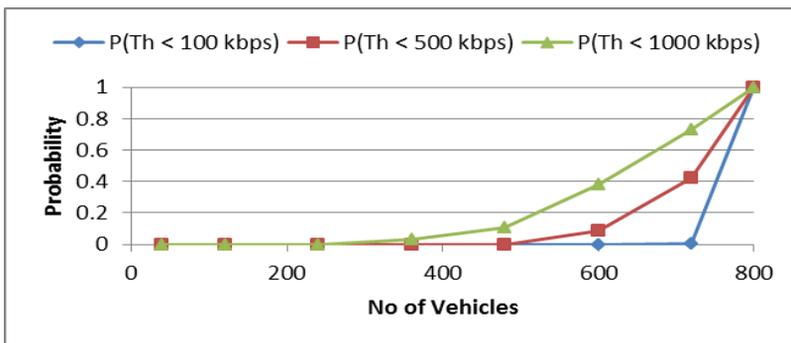

Fig. 5. Probability of a background call experiencing decreased throughput

Figure 6 shows the average end-to-end beacon delay for the different scheduling schemes used for the case of f=20 Hz. Clearly, the performance of the two dynamic schemes is almost identical except for the fact that when priority for ITS is used more vehicles can be accommodated (800 vs 720 for fair sharing), since the vehicles get all of the available PRBs. Of course that means that at the same time, the background traffic is starved and does not get any resources allocated. The performance of SPS is much worse (59 ms) due to the way that this scheme is designed and the unfortunate coincidence that in ITS the beacon generation time and the beacon delivery requirement are the same (50ms). The Semi-Persistent scheduler assigns the resources to the users, keeping in mind that it has to assign enough resources to each vehicle in order to be able to transmit one beacon every 50 ms (beaconing frequency).

The exact timing of the resources assigned to each user is random, the only restriction is, that the time interval from the beacon generation to the time were the user gets its resources, must be, under 50 ms. Unfortunately, that means that most of the time this time interval is around 35 to 40 ms and that only represents the UL buffering time. By adding the rest of the delays that a beacon encounters through the LTE network (UL transmission delay, core network delay, DL transmission delay, etc.) the end-to-end delay of the beacon adds up to around 60 ms.
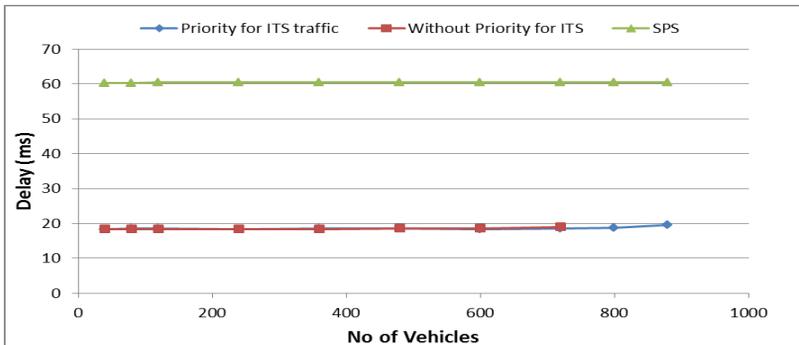

Fig. 6. Average end-to-end beacon delay for different scheduling schemes

On the other hand, SPS saves a lot of system resources compared to the two dynamic schemes, as is shown in Figure 7. As more and more users in the network use SPS (increasing number of vehicles), the less resources are needed for control signaling which means that more resources are available for actual data transmission. When the number of vehicles using SPS is very high compared to the background traffic that uses default dynamic scheduling, as little as 4% of the total system resources are necessary for control signaling. This means that when SPS is used, more users can be accommodated by the network, but the high end-to-end delay of the beacons makes this scheme unsuitable for serving the first class of ITS applications. From the results presented above, we see that LTE can meet the ITS delay requirements for a large number of ITS users (around 600 for f=10 Hz and 300 for f=20 Hz) while at the same time it provides sufficient throughput for the background traffic.
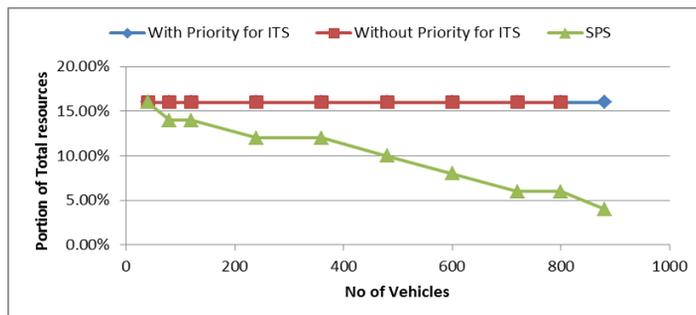
Fig. 7. Resources used for control signaling

In order to compare LTE's performance with that of 802.11p we take into account the work we carried out in [14]. By using the ITS Communication Analyzer (ITSComAn), a simulation tool developed by TNO, we were able to run simulations using 802.11p under similar conditions with those that LTE was tested under and obtain some rough results. The results show that for a network load of 450 vehicles, 802.11p exhibits an extremely low average delay, in the order of 2 ms, while the maximum delay experienced by the vehicles does not surpass 8 ms. Under the same conditions, the average delay offered by LTE is 18 ms (Figure 2).

On the other hand, when using 802.11p a large amount of beacons are lost due to interference, collisions and hidden nodes. At a distance of 50 meters from the transmitter 10% of the beacons are already lost, while at a distance of 600 meters more than 50% of the beacons are lost. Moreover, the transmission range of the vehicles is restricted to 700 meters due to the restriction in the transmission power that they can use. As we have seen in Figures 2 through 5, LTE can accommodate for a larger amount of vehicles (up to 600) with a larger transmission range and without dropping any of the transmitted beacons.

5   Conclusions

From the results presented above, we conclude that LTE can meet most of the requirements of ITS applications, as long as the network's capacity limit has not been reached. When this point is reached the performance of LTE degrades significantly and can no longer meet the ITS requirements. The latencies and capacity offered by LTE under normal network conditions, make it an ideal candidate for use in ITS and at the same time it can accommodate for the background traffic data calls, without compromising the offered QoS beyond certain acceptable limits. The implementation of Semi-Persistent Scheduling in ITS applications can offer some great advantages in terms of capacity of the system, but the fact that the beacon inter-arrival time and the beacon delivery requirement are the same in some ITS applications, make it hard to "harvest" these advantages in ITS implementations.

In comparison with 802.11p, LTE offers larger capacity and larger communication range. On the other hand, 802.11p can offer much lower beacon latencies than LTE,

due to its direct way of communication, in the case that the network is not operating close to its capacity. Moreover, LTE hardly suffers from beacon losses due to collisions, while this is a substantial problem for 802.11p.

In light of the above results we came to the conclusion that a promising solution for communications in a ITS network, would be a combination of the 802.11p and the LTE standards. The 802.11p is more suited to serve the active safety ITS applications, which have stringent delay requirements, because of its extremely low beacon latencies, while LTE is perfectly suited to serve the rest of the ITS traffic thanks to its large capacity. At the same time, since LTE will be handling a large portion of the ITS load, the 802.11p standard will have no scalability or capacity issues.

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