Scalability analysis of infrastructure networks for vehicular safety applications

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Abstract—Vehicular ad-hoc networks are able to provide the awareness among cars, which is exploited by the emergent automotive safety applications, such as lane change warning and electronic brakes. Beaconing, i.e. periodic broadcasting of status messages by each vehicle, is a core communication pattern which all the critical vehicular safety applications rely on. A set of IEEE 802.11p/WAVE (Wireless Access in Vehicular Environments) protocols is specially designed to support vehicle-to-vehicle communication. Notwithstanding, many studies raise the scalability problem of 802.11p carrier sense multiple access, which makes it impossible for the protocol to guarantee the required performance in dense road traffic scenarios. Thus, existing cellular broadband wireless access (BWA) infrastructure, e.g. 3GPP Long Term Evolution (LTE), IEEE 802.16e (Mobile WiMAX), can be considered as an additional opportunity to support vehicular cooperative safety applications. In this paper we introduce a simple stochastic model for the evaluation of the BWA network used for the beaconing. This model can serve as an easy tool to understand the theoretical limits of different BWA technologies in intelligent transportation systems use cases.

Index Terms—Automotive safety, cooperative awareness, broadband wireless access networks, beaconing, hybrid vehicular networks, VANETs.

I. INTRODUCTION

Ongoing traffic warning, electronic brake warning, merging assistant and other cooperative active safety applications rely on the ability of vehicles to communicate with each other and with infrastructure [1]. Recently, IEEE 802.11p/1609 Wireless Access in Vehicular Environments (WAVE) protocols aimed at supporting vehicle-to-vehicle communications were approved. However, both the performance of WAVE technology in particular, and socio-economic challenges of Vehicular Ad hoc NETworks (VANETs) concept in general are currently being a subject of severe studies [2].

One of the key limitations of the IEEE 802.11p is its low scalability, i.e. the protocol is unable to provide the required real-time performance in dense road situations with high number of vehicles in the same area [3], [4]. This motivates the consideration of the use of existing broadband wireless access (BWA) networks and, particularly, IEEE 802.16e (Mobile WiMAX), as a communication technology for vehicular cooperative safety systems. This paper provides an analytical framework which is based on [5], [6] and models the basic patterns of Mobile WiMAX protocol in the context of vehicular safety scenarios. The modeling approach introduced is simple, but provides clear insights into the theoretical limitations of BWA networks to support V2V communications.

The paper is organized as follows. Section II presents the mathematical model for the evaluation of the 802.16e in terms of the probability to deliver the beacon before the expiration of the deadline. Numerical results are in Section III. Section IV concludes the paper.

II. SYSTEM MODEL

A. Basic Principles

Cooperative vehicular safety applications are based on the periodic exchange of status messages also known as beacons by the cars. Beacons contain the information about the car position, its velocity and acceleration. In VANETs, which are based on 802.11p, beacons are broadcast frequently by car vehicle. Intended communication range is in the order of 300–500 meters. Thus, beaconing provides awareness about the vehicles in the vicinity. In the infrastructure-based centralized WiMAX BWA network, beaconing can be implemented as follows. All the cars in the cell transmit in the uplink channel their beacons to the base station (BS). After this, the BS transmits the beacons which are relevant to each vehicle in the downlink channel (Figure 1). To implement beaconing in this way, all the beacons are to be sent to the fixed network, where a geo-based application determines the relevant receivers for each beacon. Following the [4] the delay induced by the fixed network is ignored in the analysis.
Three strategies of the BWA network operation are examined. The first strategy assumes that the BS simply broadcasts in the downlink all the received beacons to all the vehicles in the cell ("downlink broadcast"). The other two strategies are: each received beacon is sent to every vehicle in the cell ("downlink unicast") or to every vehicle in the corresponding awareness range ("downlink unicast with filtering").

In this paper we calculate the probability of delivering the beacon before the expiration of its deadline for Mobile WiMAX BWA network. This metric can be considered as a key one for the safety-related vehicular applications [4]. The deadline is assumed to be equal to the beaconing period. The beacon is outdated and dropped, if it is not transmitted to the intended recipients, when the new one is generated by the vehicle. Therefore the beaconing delay cannot exceed the beaconing period and beacons which experience larger latencies contribute to a decrease in delivery probability.

B. Basics of IEEE 802.16e MAC

The WiMAX medium access control (MAC) layer is designed with QoS support by allowing bandwidth reservation and flexible implementation of resource scheduling. In practical scenarios beacons will be transmitted along with other types of "normal" traffic in BWA network and, therefore, proper scheduling at the BS is critical for achieving real-time beaconing performance.

Both time-division duplexing (TDD) and frequency-division duplexing (FDD) modes are supported. In the TDD case each MAC frame includes a downlink subframe followed by an uplink subframe. The Tx/Rx transition gap (TTG) and the Rx/Tx transition gap (RTG) are specified between the downlink and uplink subframes, and between the uplink and following downlink subframes in the next frame duration to allow nomadic or mobile nodes (in our case – vehicles) to turn around from reception to transmission and vice versa.

In the downlink subframe, both the downlink MAP (DL-MAP) and uplink MAP (UL-MAP) management messages are transmitted, which comprise the bandwidth allocations for data transmission in both downlink and uplink directions, respectively. Moreover, the lengths of uplink and downlink subframes are determined dynamically by the BS and are broadcast to the nodes through UL-MAP and DL-MAP messages at the beginning of each frame.

The uplink subframe contains contention period of transmission opportunities scheduled for the purpose of sending BW-REQ messages in which BW-REQ messages can be transmitted, which serves for SSs to indicate to the BS that they need UL bandwidth allocation. The BS controls both the number of transmission opportunities for BW-REQ and data packet transmission through the UL-MAP message.

With random access, a node transmits a bandwidth request (BW-REQ) during a predefined contention period, and a random backoff mechanism is used to resolve contention among nodes. Therefore, simplified IEEE 802.16e frame structure in TDD mode is presented in Figure 2.

C. Stochastic modeling

Following the approach from [6] let us assume that each frame comprises K intervals of time having duration α, which are called mini-slots and represent random access transmission opportunities and U + D intervals of time having a duration equal to one unit of time, which are called slots. Slots are used by the vehicles for transmitting beacons, while mini-slots are used for sending BW-REQ messages. U slots are allocated for the uplink data transmission, while D slots represent the downlink. The following simplifying assumptions are made in this paper:

- there are \( N_{\text{CELL}} \) vehicles in the cell and \( N - 1 \) vehicles within 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;
- management overhead and background traffic are not considered, so all the network capacity is used exclusively for the transmissions of beacons.

Let us consider a sequence of \( t \) frames during the beaconing period. For each beacon the BW-REQ has to be successfully transmitted in one of the mini-slots. If that happens, then corresponding beacon is scheduled for the transmission in the uplink. Finally, relevant beacons are delivered to each vehicle by the BS in the downlink. The following recursive relationships are valid for the beaconing in the considered system:

\[
A(1) = S(K, N_{\text{CELL}}),
A(i) = S(K, \hat{A}(i - 1)),
\hat{A}(i) = \hat{A}(i - 1) - A(i),
B(1) = \min(U, A(1)),
B(i) = \min(U, B(i - 1) + A(i)),
\tilde{B}(1) = A(1) - B(1),
\tilde{B}(i) = \tilde{B}(i - 1) + A(i) - B(i),
C(1) = \min(D, B(1)N),
C(i) = \min(D, B(i)N + \hat{C}(i - 1)),
\hat{C}(1) = B(1)N - C(1),
\tilde{C}(i) = \tilde{C}(i - 1) + B(i)N - C(i),
\]

where \( A(i) \) is the number of vehicles which successfully transmitted their BW-REQs in the \( i \)-th frame, \( \hat{A}(i) \) is the number of vehicles which has not yet successfully transmitted by the end of this frame, \( B(i) \) is the number of beacons which
have been transmitted by the vehicles in the uplink of the \(i\)-th frame and \(\bar{B}(i)\) is the number of non-transmitted beacons, the bandwidth for which has been already reserved using the BW-REQs by the end of this frame, \(C(i)\) is the number of beacons transmitted in the downlink of the \(i\)-th frame and \(\bar{C}(i)\) is the number of beacons which have not yet been transmitted by the BS by the end of this frame. \(S(k, n) = (1 - 1/k)^{n-1}\) is the mean number of BW-REQs successful transmissions per frame for the simplest random access algorithms when a uniform choice of one out of \(k\) mini-slot is done by each of \(n\) vehicles.

Finally, the target probability of beacon delivery is

\[ P = 1 - \frac{A(t)N + B(t)N + C(t)}{N_{CELL}N} \]

### III. NUMERICAL RESULTS

We conducted a series of experiments with the developed analytical models and the corresponding simulation program in MatLab for the typical beaconing parameters presented in Table 1. In our settings a vehicle generates a beacon once per one WAVE Synchronization Interval or per ten frames.

#### A. IEEE 802.11p

In this subsection we refer to the results from [4]. Probabilities of beacon delivery before the expiration of its deadline in 802.11p/WAVE for a different number of vehicles \(N\) and different values of Contention Window \(W\) are presented in Figure 4. For any \(W\) value when \(N = 50\) the target probability never exceeds 0.83, which is lower than required in typical safety applications [1].

#### B. IEEE 802.16e

For IEEE 802.16e case, probabilities of beacon delivery before the expiration of its deadline \(P\) for different number of vehicles in the cell \(N_{CELL}\) are presented in Figures 5 and 6.

### IV. CONCLUSION

It can be concluded that for studied set of simulation parameters the last two strategies (downlink unicast and downlink unicast with filtering) are appropriate for safety-related applications only for small number of vehicles in the cell (less than 100). Although the “downlink broadcast” performs better, the system becomes congested for \(N_{CELL}\) exceeding 300.

Our future work will target the design of more realistic BWA models for the study of the beaconing performance.

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Fig. 6. BWA network beaconing performance for $U=50$ and $D=950$

REFERENCES