Improved Real-Time Communication Infrastructure for ITS

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Abstract. Transportation systems play an extremely important role in modern society. A huge research effort has been devoted to this field in the past few years making them safer, cleaner and more efficient; originating the so-called Intelligent Transportation Systems (ITS). In ITS there is a closed loop interaction between vehicles, drivers and the transportation infrastructure. While some of the enabling technologies are entering their mature phase, there are still many open problems that must be solved before such systems can be effectively leveraged. One of such problems arises from the fact that many ITS services have timeliness constraints that are not fulfilled by the communication protocols proposed so far, specifically in road congestion scenarios. This paper describes a wireless vehicular communication architecture, developed in the scope of the EU FP7 ICSI project, aiming at providing a deterministic V2I/I2V communications. This paper presents a global architecture, reviews the Vehicular Time-Triggered (V-FTT) Protocol; a communication protocol based on IEEE802.11p/ITS G5 that embodies improved timeliness properties, proposing traffic scheduling and admission control mechanisms while taking advantage of roadside units connected to a deterministic backhauling network.

1 Introduction

Wireless vehicular networks for cooperative Intelligent Transport Systems (ITS) have raised widespread interest in the last few years due to their potential applications and services. Cooperative applications with data sensing, acquisition, processing and communication provide an unprecedented potential to improve road safety, passengers' comfort and traffic management. In order to support such visionary scenarios, applications running in the vehicles are required to communicate with applications in other vehicles or with applications deployed in the back office of the emergency services, road operators or public services. These applications run unattended, reporting information and taking commands from counterpart applications in the vehicle or network.

The mobile units of a vehicular network are equivalent to nodes in a traditional wireless network. Besides the ad-hoc implementation of a network consisting of neighboring vehicles; joining up and establishing Vehicle-to-Vehicle (V2V) communication; there is also the possibility of a more traditional wireless network setup with base stations along the road sides.These base stations work as access points and manage the flow of information in Vehicle-to-Infrastructure (V2I) communication. Devices operating inside vehicles are called On Board Units (OBUs) while devices operating on the side of the road are Road Side Units (RSUs).

Safety, efficiency and comfort ITS applications exhibit tight latency and throughput requirements. For example, safety critical services require guaranteed maximum latencies lower than 100 ms while most infotainment applications require QoS support and data rates higher than 1 Mbit/s. Besides latency and throughput safety applications also require deterministic communications (real-time). For example, a vehicle involved in an accident should be granted timely access to the wireless medium to transmit warning messages, even in congested road scenarios.

The IEEE 1609 family of standards for Wireless Access in Vehicular Environments (WAVE) defines an architecture and a standardized set of services and interfaces that collectively enable V2X wireless communications. Additionally, the IEEE 1609 standards rely on IEEE 802.11-2012 Amendment 6 [1] also known as 802.11p and the equivalent European standard ETSI ITS G5 [2]. The medium access control (MAC) layer adopts a carrier sense multiple access with collision avoidance (CSMA/CA), same as IEEE 802.11a but with a new additional, non-IP, communication protocol either Fast Network and Transport Protocol (FNTP) or Wave Short Message Protocol (WSMP). The non-IP protocols coexist, in parallel, with IPv6. IEEE 802.11p adopts the QoS policy of IEEE 802.11e and defines a mechanism for the dynamic switching of channels. Since the IEEE 802.11p MAC is based on CSMA; collisions may occur indefinitely due to the non-determinism of the back-off mechanism. So native IEEE 802.11p MAC alone does not support real-time communications. Nevertheless, the probability of collisions occurring may be reduced if the load of the network is kept low, which is difficult to guarantee in vehicular communications, or if some MAC protocol restricts and controls the medium access to provide a deterministic behaviour.

There are basically two main design choices to implement a scalable, fair and deterministic MAC layer for safety vehicular communications. It either could rely on the roadside units and infrastructure or it could be based on V2V communications without any road-side units support. The obvious advantage of V2V is that it does not require infrastructure which means it is cheaper and easier to deploy. However, V2V presents some strong disadvantages in what concerns safety applications [3][4]. Moreover, the road-side infrastructure can be seen as an instantiation of the *wormhole* metaphor [5]; where it is assumed that uncertainty is neither uniform nor permanent across all system components i.e. some parts are more predictable than others. In this way, the more predictable parts of the system can be seen as *wormholes* since they will execute certain tasks faster or more reliable than apparently possible in the other parts of the system. Thus, it can be argued that I2V communications could be made safer than pure V2V as the presence of the infrastructure i.e. road-side units and a backbone cabled network adds a degree of determinism needed to enforce real-time and safety at the wireless end of the network. For this purpose, we review the global architecture of the Vehicular Time-Triggered Protocol (V-FTT) [6]; a communication protocol based on IEEE802.11p/ITS G5 that embodies improved timeliness properties and propose traffic scheduling and admission control mechanisms taking advantage of roadside units connected to a backhauling network.

The rest of the paper is organized as follows. Section 2 describes some relevant work on real-time MAC protocols for wireless vehicular communications. Section 3 presents a brief overview of the V-FTT protocol. Section 4 contains the core contribution of the paper, a proposal to schedule safety messages transmission in the scope of the V-FTT protocol. Finally, Section 5 summarizes the main conclusions of the paper and unveils some future work.

2 Related work and background

This section briefly presents the main proposals found in the literature to overcome the medium access control (MAC) issues of IEEE802.11p and ETSI-G5 in what concerns real-time communications guarantees. We will focus our analysis on infrastructure-based solutions supporting V2I communications and also on spatial time division multiple access (STDMA) since the proposed solution adapts and extends some of the principles of STDMA.

2.1 Infrastructure based deterministic MAC protocols

Several authors [6][7][8] have proposed deterministic Medium Access Control (MAC) schemes for V2I communications by extending the IEEE 802.11-A6 [9] commonly known as IEEE 802.11p standard. In 802.11p there is a a collision-free communication phase controlled by an access point as provided in other 802.11 instances. This collision-free phase needs support from a coordinator, in this case a Road Side Unit (RSU), which takes the responsibility of scheduling the data traffic and polling the mobile nodes. In this way the channel is assigned to each vehicle equipped with an On Board Unit (OBU) for a specific period of time and real-time data traffic is scheduled in a collision-free manner by each RSU.

Meireles *et al.* [6][8] proposal has a lower overhead compared to individual pool-reply scheme adopted in [7] as it transmits the schedule of multiple OBU transmissions in a single RSU message. Meireles *et al.* [8] protocol called the vehicular flexible time-triggered (V-FTT) adopts a master multi-slave time division multiple access (TDMA) in which the road-side units act as masters and schedule the transmissions of the on-board units. This protocol has some interesting properties like dynamic online scheduling; in which there is the possibility of adopting multiple scheduling policies, strict event and time-triggered traffic isolation and online admission control.

Böhm and Jonsson[7] assign each vehicle an individual priority; based on its geographical position, its proximity to potential hazards and the overall road traffic density. This is done by introducing a real-time layer on top of the normal IEEE 802.11p. A super frame is created in order to obtain a Collision Free Phase (CFP) and a Contention Based Period (CBP). In the CFP the RSUs assume the responsibility of scheduling the data traffic and polls mobile nodes for data. Vehicles then send their heartbeats with position information and additional data (such as speed, intentions, etc.). The RSU sends a beacon to mark the beginning of a super frame, stating the duration of the CFP, so that each vehicle knows when the polling phase ends and when to switch to the regular CSMA/CA from IEEE 802.11p, which is used in the CBP, along with the random backoff mechanism similar to IEEE 802.11e. The length of CFP and CBP is variable. Real-time schedulability analysis is applied to determine the minimum length of CFP such that all deadlines are guaranteed. The remaining bandwidth is used for best-effort services and V2V communications. In order for RSUs to start scheduling vehicle transmission, vehicles must register themselves by sending out connection setup requests (CSR) as soon as they can hear an RSU. This is done in the CBP, so a minimum risk exists of vehicles failing to register. They can, however, receive information from RSUs and communicate using the CBP. Böhm refers that vehicles might want to increase the number of heartbeats sent during lane change or in certain risk areas, but this is not clearly explained. Another interesting issue is that a proactive handover process is defined, based on the knowledge of road path and RSUs locations. Nothing is mentioned about RSU coordination and how it is done.

Bohm's protocol has many similarities with Tony Mak *et al.* [10] who proposed a variant to 802.11 Point Coordination Function (PCF) mode so that it could be applied to vehicular networks. A control channel is proposed in which time is partitioned into periodic regulated intervals (repetition period). Each period is divided into a contention free period also named CFP by the author (with the same meaning as Collision Free Phase used by Böhm) and an unregulated contention period. The scheme is similar to Böhm's; where each vehicle is polled by an RSU or Access Point (AP) during the CFP; similarly to the PCF of a regular IEEE 802.11. Vehicles need to register and deregister so the polling list is kept updated. For this purpose a group management interval is created so that vehicles entering and leaving the region can notify the RSU. However this beacon is sent in the CP and contends with other communications. The authors propose that the beacon is repeated to decrease probability of reception failure of the beacon. No schedulability analysis is made in [10] but the authors claim that the time between consecutive polls for vehicles in the RSU coverage area is bounded.

As it was argued in the previous section, the roadside infrastructure can be seen as an instantiation of the *wormhole* metaphor, thus it will execute certain tasks faster or more reliably than apparently possible in the other parts of the system. To materialize such assumption, one needs to make sure that the backhauling network is deterministic. There are two complementary ways to secure determinism (real-time) in the roadside network necessary for RSUs' coordination i-e: use a real-time network technology, usually at Layer 2, or employ resource reservation protocols to extend the guarantees to multiple networks and to higher layers. Further details on these issues are out of the scope of this paper.

2.2 Overview of spatial TDMA

Real-world scenarios often require the use of multiple RSUs; not only to cover wide geographical areas but also to cover the existence of natural or artificial obstacles that usually block or hinder the communications. Since the density of vehicles is usually high in urban areas, it is also important to use the available bandwidth in an efficient manner. Spatial reuse of communication slots in wireless TDMA architectures (STDMA) first proposed in [11]; has since been studied extensively, including scenarios in which real-time service guarantees are sought. The underlying idea is increasing the communication capacity by permitting, when possible, concurrent transmissions in the same slot as issued by different nodes. The slot sharing is possible when the nodes are geographically separated and the resulting interference is small.

Although simple in concept, the problem of obtaining STDMA schedules that met specific application constraints is far from trivial. In fact, the simple minimization of the TDMA cycle in packet radio networks was proven to be an NP-Complete problem [12].

The basic approach for building a conflict-free TDMA schedule starts by identifying the links between every source and destination nodes, as well as the communication requirements (number, size and temporal characteristics of the messages). Then using appropriate channel information, the interfering/conflicting links are identified. Afterwards an appropriate algorithm is used to generate the TDMA schedules subject to some specific criteria (e.g. minimizing the TDMA cycle, minimizing the lateness, etc.).

A plethora of STDMA based schedule generating algorithms, both centralized and distributed in terms of coordination, can be found in literature. E.g. [13] proposes a centralized algorithm based on neural networks while Pond *et al.* [14] proposes a distributed protocol by considering multi-hop TDMA broadcast packet radio network. Lloyd *et al.* [15] presents an algorithm aiming at generating minimum schedules by considering both the link and node scheduling cases.

Hafeez *et al.* [16] proposes a "high spatial-reuse distributed slot assignment protocol" in which nodes compute the slot assignment based on local topological data. Nodes are granted slots according to their number of neighbors thus implementing a priority scheme.

More recently there was an effort to address more realistic channel models. Two categories are usually considered: protocol interference model and physical interference model. In the former model the communication between two nodes i-e s (sender) and r (receiver) is considered successful if there are no concurrent transmissions in a predefined interference range of node r. The physical interference model is more realistic since it considers a transmission successful only if the Signal to Interference and Noise Ratio (SINR) at the receiver v is above a certain threshold. This model is more realistic since it accounts for the interference of several nodes in the channel but only at the expense of greater complexity. Xue *et al.* [17] proposes greedy algorithm for link scheduling by considering the physical interference model, which improves the greedy approach presented in [18].

Another recent research line that has recently drawn the attention of the scientific community and which is closely related to the work in this paper is the link allocation routing and scheduling in hybrid networks. For instance in [19] they proposed a methodology to optimize the throughput by placing free space optics links at appropriate places and deriving the routing and schedules in an integrated manner.

As discussed above, STDMA is a deeply studied subject with abundant results. However, the V2I/I2V scenario addressed in this paper has a combination of features and requirements that are unique and distinctive. More specifically:

- Due to the fast mobility of vehicles, the schedule must constantly be updated so a computationally complex algorithm cannot be used;
- It is also possible to predict, to some extent, the position of vehicles in near future. Such information can be used in the schedule update;
- The system has global knowledge. Different RSUs share information in real-time. The system may perform both in a distributed or centralized manner;
- The communication is exclusively broadcast and single-hop;
- The scheduling is carried out over nodes, not links;
- Messages have distinct priorities
- Messages and slots have all the same size;

None of the research work found so far in the literature addresses such combination of issues in an integrated manner, thus opening a way for further research in the context of infrastructure-assisted wireless vehicular networks.

3 Brief overview of the V-FTT protocol

Recently, a proposal for deterministic medium access control (MAC) for vehicular environment was presented in [6] called the "vehicular flexible time-triggered (V-FTT) Protocol". This protocol adopts a multi-master multi-slave spatial time division multiple access (STDMA) in which the road-side units act as masters and schedule the transmissions of the on-board units. As depicted in Fig 1, the protocol is divided into periodic elementary cycles (ECs) where each EC starts with an infrastructure window (I2V) containing trigger and warning messages.

The V-FTT protocol inherits most of its concepts from the original Flexible Time-Triggered protocol definition [20]; while adds some new features to it to cope with the wireless vehicular scenario. In particular it adopts redundant scheduling for OBUs transmissions to increase reliability and to cope with the variations of the propagation patterns of the RSUs caused by atmospheric and traffic conditions. According to the proposed redundant scheduling scheme, a single OBU is scheduled by a configurable number of RSUs, for the same transmission slot. As RSUs cooperate to schedule OBUs safety communications, they must be able to coordinate their own transmissions, avoiding possible mutual interferences. To support RSU coordination, it is assumed that they are fully interconnected by a backhauling network. It is also assumed that RSUs are able to receive messages from vehicles travelling in both directions and vehicles can receive messages from various adjacent RSUs.

Each RSU will transmit its Trigger Message (TM) in its transmission slot to schedule the OBUs transmission slots, using just one message. This scheme is known as master multi-slave; as a single master (RSU) message triggers the transmission of a number of slave (OBU) message as opposed to the traditional master-slave in which each master message triggers just one slave reply. As a configurable number of RSUs cooperate to redundantly schedule the transmissions of the same OBU, it can be said that V-FTT adopts a multi-master multi-slave spatial TDMA. In this RSU coordination proposal, RSUs transmit the OBUs scheduling in a reserved window called the Infrastructure Window. Within this window time slots are reserved for each RSU. As RSUs are synchronized, they are able to respect the time slot boundaries.

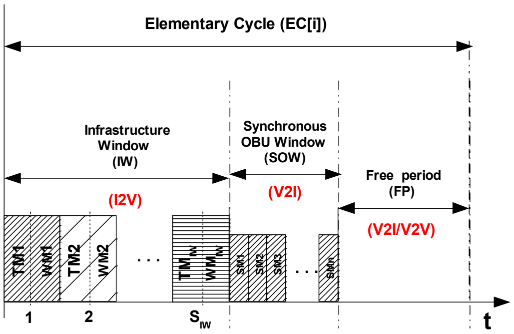

Fig. 1. Elementary Cycle of Vehicular Flexible Time-Triggered protocol [8].

The infrastructure window is followed by the synchronous OBU window where OBUs have the opportunity to transmit information to RSUs (V2I). Each OBU will have a fixed size slot to transmit vehicle's information (speed, acceleration, heading, etc) and/or a safety event. The Synchronous OBU Window duration is variable. The elementary cycle ends with an optional free period window, a period where non V-FTT enabled OBUs are able to transmit safety messages and RSUs and OBUs are able to transmit non-safety messages.

In V-FTT, roadside units are responsible for two main operations:

- To schedule the transmission instants of the vehicle OBUs in what concerns the safety frames they have to broadcast.
- To receive information from the OBUs, edit that information and publish the edited safety information in the adequate places and instants (might be a broadcast or might be a communication to selected vehicles(s)).

From the communications point of view, the OBUs must:

- Listen to the RSU transmissions (at least one RSU should be heard), retrieve the safety information and dispatch these information.
- Always transmit its specific safety frame in the time window allocated by the RSUs.

Constant sized Cooperative Awareness Messages (CAM) [21] are transmitted during the Synchronous OBU Window. CAM messages are broadcast messages that include several possible data elements (e.g., CrashStatus, Dimension, Heading, Latitude, Longitude, Elevation, Longitudinal Acceleration, Speed). CAM messages are transmitted periodically and have strict timing requirements. They are generated by the CAM Management and passed to lower layers according to some set of rules [21] which are checked every 100ms. A CAM message is dropped whenever the channel access request does not result in actual channel access before the next message is generated. There will be temporary reduction in the performance efficiency of the application if a periodic message misses its time limit.

Non-registered OBUs will also receive safety information from RSUs. However, they are not able to transmit information according to the proposed protocol, although they can still contend for transmission during the free period, but without any guarantees.

The information broadcast by the RSUs must be trustworthy, so RSUs must validate OBUs' events before being broadcasted to vehicles. This validation must obviously be performed in bounded time so that the results could be transmitted to the OBUs in real-time.

Road segments covered by RSUs running the V-FTT protocol are called Safety Zones (SZ). Whenever a vehicle enters a SZ, it registers itself with the infrastructure so that RSUs could assign an identifier to each vehicle (OBU) and schedule their transmissions. The responsibility of scheduling vehicles moving along a road equipped with a roadside infrastructure is passed from RSU to RSU in a cooperative and distributed way. This handover process must also be dependable and timely.

4 Traffic scheduling

The deployment of safety wireless vehicular communications in the scope of ITS applications supported by roadside backhauling networks requires an end-to-end deterministic behaviour. For example, a vehicle involved in an accident should be granted timely access to the wireless medium to transmit a safety message, which once validated by the roadside infrastructure, should trigger the timely transmission of warning messages to other vehicles approaching the accident site. Therefore, it is important to have a proper scheduling of the communication channel to allow critical information to be transmitted with minimum latency. Moreover, the vehicles close to the accident or driving in its direction could be within the coverage area of different RSUs; each enforcing a real-time MAC protocol for the vehicles in their coverage area. In this scenario the responsibility of scheduling the vehicle transmissions is passed to nearest RSU; thus requiring deterministic handover to extend the local (RSU) real-time guarantees to the whole roadside infrastructure.

V-FTT provides a deterministic MAC protocol to support the real-time guarantees as mentioned above. The next sections present an analytic framework that enables managing the traffic appropriately.

4.1 Problem statement and system model

In this paper a geographical region covered by one or more RSUs is considered. The RSUs are interconnected by a deterministic real-time network. Vehicles that are managed by the system integrate an OBU. Vehicles traveling in urgent mission such as ambulances, police and fire fighters receive privileged access. Moreover, vehicles that are involved in accidents and/or that report information about accidents or other abnormal events also receive privileged access to the communication channel. The temporal validity of the information is variable, therefore there is an associated deadline.

More formally, the system under consideration can be described as follows.

$$R = \{RSU_1, RSU_2, ..., RSU_N\}, N \geq 1 \tag{1}$$

R is the set of N RSUs that cover some geographical region A. Each RSU covers a given sub area A_i, such that $A = \{A_1 \cup A_2 \cup ... \cup A_n\}$. Due to the high dynamics of the system (vehicles may travel at a relatively high speed) and the high number of vehicles that may have to be managed, a simpler protocol interference model is adopted instead of a more accurate, but complex, physical interference model. Consequently, in scenarios with multiple RSUs, it is possible to define a binary matrix I, which defines the interference ranges, as illustrated in Table 1. This table assumes the existence of 4 RSUs with a homogeneous range, in which each cell may interfere with the adjacent ones. Thus, $I(i,j) = 1$ if a vehicle in area A_i, covered by RSU_i may interfere with a vehicle in area A_j, covered by RSU_j, and vice-versa.

The diverse sub areas overlap partially meaning that OBUs may be in the communication range of more than one RSU. OBUs have an individual and unique identifier (ID) and send CAM messages that contain a system-wide fixed amount of data (W bytes), which take C seconds to transmit.

The V-FTT protocol is configured with a fixed EC duration of $LEC = 100ms$, which corresponds to synchronization interval of IEEE 1609.4. The SOW

R4	0	0	1	1
R3	0	1	1	1
R2	1	1	1	0
R1	1	1	0	0
RSU	R1	R2	R3	R4

Table 1. Interference Range Matrix

window is configured to accommodate up to S safety messages, each one assigned to a slot of size C. Slot size and message size are equal to impede the transmission of alien (i.e. non V-FTT) messages during the SOW.

The set of nodes in the covered area generates a message set M as follows:

$$M = \{m_i, m_i = \{ID_i, X_i, C, T_i, P_i, D_i\}\}, i = 1..O \tag{2}$$

ID represents the unique OBU identifier, $X_i \in A_i$ the vehicle position, T_i the message periodicity, P_i the message priority, D_i the deadline and O is the number of OBUs in the system. Note that T_i, P_i and D_i are the dynamic parameters that are managed by the system according to the vehicle conditions and the overall system load.

4.2 Basic problem - single RSU

The model used to schedule synchronous OBU messages (CAM) traffic in V-FTT is very similar to the one presented in [20]. According to this model message periods and deadlines are integer multiples of a basic cycle duration (LEC) where message transmission times are shorter than LEC. Message activations are always synchronous with the start of the cycle and the synchronous traffic is confined to a sub-window of the EC with maximum length $L = S * C$.

As shown in [20], a simple technique to model the effects mentioned above is to inflate the message transmission times by a factor equal to $\frac{LEC}{L}$, which is equivalent to expanding the SOW up to the whole EC. Applying this transformation to the original message set results in a new virtual set (M^v) as defined in Equation 3, where all the remaining parameters except the transmission time are kept unchanged. Since all CAM messages have size C, this adaptation only requires one simple computation carried out once, independently of the number of vehicles in the area.

$$M^v = \{M_i, M_i = \{ID, X_i, C^v, T_i, P_i, D_i\}\}, i = 1..O, C^v = C * \frac{LEC}{L} \tag{3}$$

CAM messages coming from priority vehicles are more important and are thus transmitted as often as possible. Thus, there is a direct association between the priority of messages and its rate, resulting in the adoption of an implicit Rate-Monotonic priority assignment. This observation, together with the transformation shown in Equation 3, allows the use of the simple Liu & Layland utilization test [22], indicated in Equation 4.

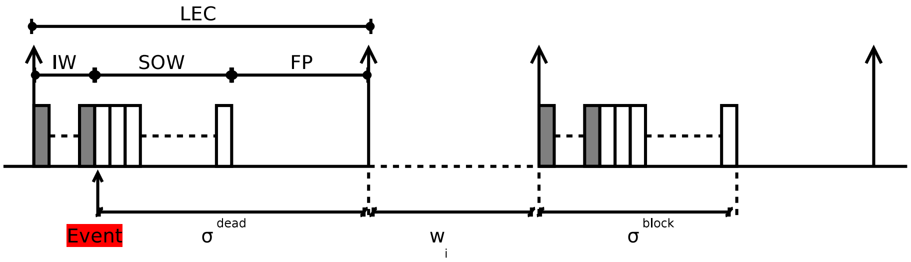

Fig. 2. Event delay components

$$\sum_{i=1}^{O} \left(\frac{C^v}{T_i} \right) < O(2^{\frac{1}{O}} - 1) \tag{4}$$

With the same adaptation the use of some other eventually more exact schedulability tests such as Response Time Analysis is also possible. The adaptation is fairly standard and is shown in Equations 5 and 6. The absence of a blocking term due to the synchronous activation of CAM messages is noticeable.

$$R_{wc_i} = I_i + size(IW) + C^v \tag{5}$$

$$I_i = \sum_{k \in hep(i)} (\lfloor \frac{I_i}{T_k} \rfloor + 1) * C^v \tag{6}$$

As usual, Equation 6 is iterated until convergence ($I_i^j = I_i^{j-1}$) or until a deadline is violated ($R_{wc_i} > D_i$). The term $size(IW)$, present in Equation 5, models the fact that CAM messages are confined to the SOW window, which always follow the IW in EC.

The worst-case response time for events can be deduced from the message worst-case response time as computed in Equation 5. Events are generated by the environment and are asynchronous with respect to the V-FTT network. Therefore, any event that happens after the transmission of the CAM message of the associated node has to wait for the activation of the next CAM message before entering in arbitration. This delay corresponds to a dead time designated as σ_i^{dead}. Then, the node has to wait a given number of ECs, due to interference, as computed in Equation 5. Finally, in the last EC it may be transmitted in any slot **within the SOW**. So, the worst case delay happens when it is assigned the last slot(σ_i^{block}). Figure 2 illustrates the origin of the dead and block times for a simple scenario in which the CAM message has a period of one EC. Therefore, the computation of the worst-case response time of an event j associated with a node i is given by Equations 7, 8 and 9.

$$Rwc_i^j = \sigma_i^{dead} + w_i + \sigma_i^{block} \tag{7}$$

$$\sigma_i^{dead} \leq LEC - size(IW) + T_i - 1 \tag{8}$$

The worst case dead time happens if the transmission of the CAM message is carried out in the first slot of the first EC after the CAM message activation. In this case the event has to wait part of the first EC ($LEC - size(IW)$) plus the remaining ECs ($T_i - 1$), as indicated in Equation 8.

$$\sigma_i^{block} \leq size(IW) + L \tag{9}$$

In reality CAM messages are confined to the SOW window. Thus, Equation 5 is pessimistic as it allows CAM messages to be scheduled at any point of the EC due to the use of inflated message times. To reduce this pessimism, it is possible to use Equation 5 to compute the integer number of ECs due to interference from high or same priority messages (w_i). The worst case delay, suffered by the CAM message in the last EC, happens if this message is the last one of the SOW, a value upper bounded by Equation 9. The integer number of ECs due to the interference is given by Equation 10.

$$w_i = \lfloor \frac{Rwc_i}{LEC} \rfloor * LEC \tag{10}$$

Both methods above allow evaluating the schedulability of a message set, thus can be used for admission control.

4.3 Realistic scenario - Multiple RSUs

As mentioned above, due to the high dynamics of the system and the potentially high number of vehicles that must be managed concurrently; it is mandatory to select expedite techniques suitable for real-time operation. That is why the protocol interference model is adopted instead of the physical interference model.

The network is represented by a graph $G = (V, E)$ such that V represents the vertices (nodes i.e, OBUs and RSUs) and E is the set of edges (wireless links between OBUs and RSUs). It is assumed that all edges are bidirectional.Thus for any two distinct vertices $\{i, j\} \in V$, $\{i, j\} \in E$ if i and j can communicate with each other.

As nodes are the basic entities of the system a node assignment scheme is adopted. The objective is to derive a schedule that will guarantee a conflict free node transmission. Slot reuse mechanism is also adopted in order to increase the number of vehicles in the system.

Let us define Z as an arbitrary set of nodes. Let us also define $\Psi(z)$ as the set of logical neighbours of a node such that $z \in Z$, indicating the set of nodes that reach the same RSU as node z is registered with, generating a transmission conflict. A necessary condition to permit the allocation of the same slot to the nodes in Z is:

$$Z \cap \Psi(Z) = \phi \tag{11}$$

That is, no two nodes in Z can reach the same RSU. The computation of $\Phi(Z)$ is easily carried out from the Interference matrix as defined in Section 4.1, and from the message set M (Equation 2, which define respectively the conflicts between adjacent areas and the area in which each vehicle is positioned).

As mentioned in Section 2, the problem of finding a slot allocation is NP-Complete. There are some heuristics in the literature but they are not directly applicable to this scenario, as they don't address multi-hop networks nor application-defined priorities. For this reason, we propose here an algorithm that takes into consideration these constraints.

Algorithm 1 Slot Assignment for Multiple RSUs

Inputs
R: set of RSUs
M: message set
S: maximum number of slots on SOW
I: interference matrix

Outputs
Sched[R,S]: array of CAM IDs (EC schedule)

```
Sched=$\phi$
Sort M by priority
For each message $m_i \in M$
  if $m_i$ is ready and $d_i \leq D_i$
    $R^u = R^{main} \cup R^I$
    For each $s \in [1 : S]$
      Found = TRUE
      For each $r \in R^u$
        If $Sched[r, s] \neq FREE$
          Found = FALSE
        endIf
      endFor
      If Found == TRUE
        For each $r \in R^u$
          $Sched[r, s] = ID_i$
        endFor
        Break
      endIf
    endFor
    If Found == FALSE return NON_SCHED
  endIf
endFor
```

Algorithm 1 takes as its inputs a set of system configuration parameters (set of RSUs, maximum number of CAM slots in the SOW and the interference matrix) and the dynamic state of the system as defined by the message set. The output of the algorithm is a matrix (*Sched* matrix) that contains the set of message IDs corresponding to CAM messages; that shall be scheduled by each

RSU in the following EC. Due to the possibility of slot reuse, *Sched* takes a matrix form since its contents may vary from RSU to RSU.

The first step is sorting the messages by priority (line 2) assuring that the highest priority nodes are privileged. Then each ready message m_i is processed (lines 3,4). Now the interference range (R_u) of each message m_i is defined (line 5). Then the availability of the slots in the adjacent interfering RSUs is identified (lines 7-12). If slot is available; it is allocated to the message m_i (lines 13-16) otherwise a Non-Sched message m_i is returned (line 20). It should be noted that the above algorithm executes concurrently in all the RSUs.

For illustration, let us consider the scenario of four RSUs presented in Table 1. Let us consider that each RSU has five vehicles in its coverage area so the total number of nodes are ($V_1 ... V_{20}$) . Without spatial reuse it would be necessary to use a total of 20 slots (one per vehicle/CAM message) in each RSU.

Assuming, without loss of generality, that priorities are $Pr(V_1) \geq Pr(V_2) .... \geq Pr(V_{20})$. So Algorithm 1 results in the following slot assignment:

RSU1
Slots 1...5 assigned to $V_1 ... V_5$ (under direct management)
Slots 6...10 assigned to $V_6 ... V_{10}$ (interference region)

RSU3
Slots 1...5 assigned to $V_1 ... V_5$ (interference region)
Slots 6...10 assigned to $V_6 ... V_{10}$ (under direct management)
Slots 11...15 assigned to $V_{11} ... V_{15}$ (interference region)

RSU3
Slots 6...10 assigned to $V_6 ... V_{10}$ (interference region)
Slots 11...15 assigned to $V_{11} ... V_{15}$ (under direct management)
Slots 1...5 assigned to $V_{16} ... V_{20}$ (interference region)

RSU4
Slots 6...10 assigned to $V_{11} ... V_{15}$ (interference region)
Slots 1...5 assigned to $V_{16} ... V_{20}$ (under direct management)

As can be seen the number of assigned slots were reduced significantly. RSU{1,4} use only 10 slots each while RSU{2,3} use only 15 slots each. Thus the bandwidth used is reduced from 25% to 50%; making it possible to accommodate more vehicles into the system and/or free bandwidth for other traffic classes and ultimately adding to the overall system capacity and throughput.

5 Conclusion

This paper presented a proposal for scheduling safety messages in the scope of wireless vehicular communications based on the Vehicular Time-Triggered Protocol. The proposed solution is an instance of the spatial time division multiple access MAC technique that relies on a deterministic network of road side units. Related work was analyzed and the Vehicular Flexible Time Triggered Protocol; which is an adaptation of the FTT protocol to wireless vehicular communications; was briefly discussed. V-FTT protocol guarantees road safety, data privacy and safety events timeliness in high vehicle density scenarios.

The proposed scheduling policy aims to increase the reliability of the safety messages transmission through the adoption of redundant scheduling while minimizing its impact on the bandwidth utilization by the implementation of slot reuse. For that purpose a slot assignment algorithm for multiple RSUs scenario was described.

Future work includes the definition of new heuristics to improve slot reuse, the design of a protocol to handle vehicles' registration when entering on a safety zone and a deterministic mobility mechanism to handover OBU's sessions between adjacent RSUs.

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References

1. IEEE, "IEEE Standard for Information technology – Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," 2012.
2. ETSI, "Final draft ETSI ES 202 663 V1.1.0 (2009-11), ETSI Standard, Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band," November 2011.
3. A. Böhm and M. Jonsson, "Real-time communication support for cooperative, infrastructure-based traffic safety applications," *International Journal of Vehicular Technology*, vol. 2011, no. Article ID 541903, pp. 17–, 2011.
4. V. Milanes, J. Villagra, J. Godoy, J. Simo, J. Perez, and E. Onieva, "An intelligent v2i-based traffic management system," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, no. 1, pp. 49–58, 2012.
5. P. Veríssimo, "Uncertainty and predictability: Can they be reconciled?" in *Future Directions in Distributed Computing.* Springer-Verlag LNCS 2584, May 2003, pp. –.
6. I. F. 317671, "Design and performance evaluation of a real-time MAC for IEEE 802.11p - D3.1.1: Fundamental Design Decisions of the Deterministic MAC Protocol," http://www.ict-icsi.eu/deliverables.html, online, as in June 20 2014, 2013.
7. A. Böhm and M. Jonsson, "Handover in IEEE 802.11p-based delay-sensitive vehicle-to-infrastructure communication," Halmstad University, Embedded Systems (CERES), Tech. Rep. IDE - 0924, 2009.
8. F. J. Meireles T., Fonseca J., "Vehicular Flexible Time-Triggered Protocol (V-FTT), Technical Report - 01/2003, Embedded System Group, Instituto de Telecomunicações, Aveiro, Portugal," 2013.

9. IEEE, “802.11-2012 - IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” 2012.
10. T. K. Mak, K. P. Laberteaux, and R. Sengupta, “A multi-channel vanet providing concurrent safety and commercial services,” in *Proceedings of the 2nd ACM International Workshop on Vehicular Ad Hoc Networks*, ser. VANET ’05. New York, NY, USA: ACM, 2005, pp. 1–9. [Online]. Available: http://doi.acm.org/10.1145/1080754.1080756
11. R. Nelson and L. Kleinrock, “Spatial tdma: A collision-free multihop channel access protocol,” *Communications, IEEE Transactions on*, vol. 33, no. 9, pp. 934–944, Sep 1985.
12. G. O. M. S. Even, S. and P. Tong, “On the np-completeness of certain network testing problems,” *Networks*, vol. 14, pp. 1–24, Sep 1984.
13. N. Funabikiy and Y. Takefuji, “A parallel algorithm for broadcast scheduling problems in packet radio networks,” *Communications, IEEE Transactions on*, vol. 41, no. 6, pp. 828–831, Jun 1993.
14. L. Pond and V. Li, “A distributed time-slot assignment protocol for mobile multihop broadcast packet radio networks,” in *Military Communications Conference, 1989. MILCOM ’89. Conference Record. Bridging the Gap. Interoperability, Survivability, Security., 1989 IEEE*, Oct 1989, pp. 70–74 vol.1.
15. S. Ramanathan and E. Lloyd, “Scheduling algorithms for multihop radio networks,” *Networking, IEEE/ACM Transactions on*, vol. 1, no. 2, pp. 166–177, Apr 1993.
16. M. Chaudhary and B. Scheers, “High spatial-reuse distributed slot assignment protocol for wireless ad hoc networks,” in *Communications and Information Systems Conference (MCC), 2012 Military*, Oct 2012, pp. 1–8.
17. D. Yang, X. Fang, N. Li, and G. Xue, “A simple greedy algorithm for link scheduling with the physical interference model,” in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, Nov 2009, pp. 1–6.
18. G. Brar, D. M. Blough, and P. Santi, “Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks,” in *Proceedings of the 12th annual international conference on Mobile computing and networking*, Los Angeles, CA, USA, Sept 2006.
19. Y. Tang and M. Brandt-Pearce, “Link allocation, routing, and scheduling for hybrid fso/rf wireless mesh networks,” *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 6, no. 1, pp. 86–95, Jan 2014.
20. L. Almeida, P. Pedreiras, and J. Fonseca, “The ftt-can protocol: why and how,” *Industrial Electronics, IEEE Transactions on*, vol. 49, no. 6, pp. 1189–1201, Dec 2002.
21. ETSI, “Technical Specification 102 637-2: Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, v.1.2.1,” March 2011.
22. C. Liu and J. Layland, “Scheduling algorithms for multiprogramming in a hard-real-time environment,” 1973.