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WiMAX Double Movable Boundary Scheme in the Vehicle to Infrastructure Communication Scenario

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Abstract WiMAX is an interesting technology that will be applied in vehicular networks due to the provisioning of high mobility, wide coverage, and different classes of service. In this paper, we investigate the problem of vehicular applications mapping in the Vehicular to Infrastructure scenario and propose a resource allocation algorithm applied in WiMAX networks. The proposed algorithm is a double movable boundary scheme which is based on dynamic sharing of resources between different traffic categories provided by a common resource pool. We provide as well a mathematical model of the mechanism and investigate the impact of critical resource allocation parameters on the overall performance. Performance results show that the algorithm respects the priority of real-time connections and prevents least-priority classes starvation problem. In fact, we strive to achieve two major components: fairness to different classes of service and service differentiation.

Keywords WiMAX · Quality of service · Scheduling · Intelligent Transportation System

1 Introduction

Vehicular networks have been attracting an increasing attention by industry and research community due to important services provided to the Intelligent Transportation Systems

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(ITS). ITS were identified as a key technology to promote increased safety, improve the national transportation infrastructure, and provide sophisticated information service to road users. Since numerous information (i.e., emergency messages, rich media content, infotainment data, etc) is exchanged between vehicles and roadside infrastructure, Vehicle to Vehicle Communications (V2V) and Vehicle to Infrastructure communications (V2I) become two important components of the ITS.

Several wireless network technologies will pave the way to the ITS communication systems. While IEEE 802.11p is the proposed standard for physical and MAC layer of V2V communications, IEEE WiMAX /802.16e may be advocated for V2I communications.

WiMAX or Worldwide Interoperability for Microwave Access is a broadband wireless technology designed for provisioning high-speed data access over long distances and based on the IEEE 802.16 standards [1,2]. It is widely believed that WiMAX will be a possible candidate for V2I communications due to the provisioning of high mobility, wide coverage, and different classes of service.

However, due to the characteristics (high mobility) of the vehicle and several factors like quality of service (QoS) requirements of real-time traffic and the provision of reliable data transmission, wireless communications are challenging for the network operator in vehicular networks.

Even though the physical layer specifications and the MAC protocol signalling are well defined in the standard [1], the resource allocation and admission control policies for the IEEE 802.16 air-interface remain as open issues. Thus, quality of service provisioning in WiMAX networks is an imperative and challenging problem to resolve.

In [3], we have proposed a Double Movable Boundary Scheme (DMBS) and applied it on the downlink in WiMAX networks. The interest of the DMBS allocation scheme lies in the dynamic sharing of resources between different traffic categories provided by a common resource pool. This helps in relaxing the congestion conditions of a certain traffic at asymmetrical offered loads while permanently preserving a certain minimum number of resources for each category. Better channel utilization is then achieved while guaranteeing a certain quality of service for each traffic.

Performance evaluations show that DMBS reduces real-time traffic delay and blocking probability and increases bandwidth usage while respecting real-time traffic requirements. In [3], we tackled two classes of service: Unsolicited Grant Service (UGS) and Real-Time Polling Service (rtPS). In the present paper, we deal with Non-Real-Time Polling Service (nrtPS) and rtPS for vehicular applications; the choice of these classes of service is justified in Section IV (D). Moreover, we extend the study: we apply DMBS in V2I context and propose an original mapping of vehicular applications to WiMAX applications. We elaborate a mathematical model of the mechanism, generalize the traffic model by taking into account the burstiness through a MMPP model. We highlight as well the impact of resource allocation parameters on the network performance.

The rest of this paper is organized as follows: Section 2 exhibits applications envisioned for vehicular networks. In Sect. 3, we introduce IEEE 802.16 Medium Access Control (MAC) layer and present the vehicular applications mapping to WiMAX classes of service.

Section 4 highlights the DMBS algorithm applied in WiMAX networks for V2I infrastructure. In Sect. 5, we present the mathematical model conducted for DMBS. Section 6 exhibits the simulation results that evaluate the performance of the proposed scheme. Finally, we conclude the paper in Sect. 7.

2 Vehicular Applications

Vehicle networks open the door for a plethora of applications and services ranging from automated highway systems to distributed passengers teleconference. These applications may be classified to safety and non-safety applications.

Safety applications [4] have attracted considerable attention since they are directly related to minimizing number of accidents on the road. On the other hand, comfort (non-safety) applications may include real-time road traffic estimation for trip planning, high-speed tolling, collaborative expedition, information retrieval, and entertainment applications.

It is noteworthy that our technical study deals with two important applications: traffic management and Web applications. In fact, we believe that vehicular traffic congestion is recognized to induce transportation costs, incremental delay, driver stress, crash risk and pollution resulting from interference between vehicles in the traffic stream, particularly as a road system approaches its capacity. Therefore, vehicular traffic should be regulated and managed to ensure smooth traffic flow, even at peak times.

On the other hand, entertainment applications deserve to be studied. In fact, statistics confirm that wireless users have need of these types of applications in order to improve their travel comfort, run some important classes of service (email, web, etc), and download commercial data that may be relevant for them.

Next, we make a survey of different types of applications and bring the focus to applications requiring vehicle-to infrastructure communications: this is due to our interest to WiMAX integration into the vehicular network.

2.1 Comfort (Non-Safety) Applications

The general aim of these applications is to improve passenger comfort and traffic efficiency. The important feature of comfort applications is that they should not interfere with safety applications. In this context traffic prioritizing and use of separate physical channels is a viable solution.

Comfort applications consist of in-vehicle entertainment, vehicular sharing, cargo, and traffic management applications.

2.1.1 In-Vehicle Entertainment Applications

These applications provide passengers with audio and video data obtained from other vehicles or the infrastructure. All kinds of applications, which may run on top of TCP/IP stack might be applied here, e.g. online games or instant messaging.

Another application is reception of data from commercial vehicles and roadside infrastructure about their businesses (wireless advertising). Enterprises (shopping malls, fast foods, gas stations, hotels) can set up stationary gateways to transmit marketing data to potential customers passing by.

2.1.2 Vehicular Sharing Applications

Vehicular sharing applications distribute data or computations on vehicles. One interesting application is the measurement of road aggregate carbon foot-print in real-time using distributed vehicle computing resources.

2.1.3 Cargo Applications

- *Vehicle registration, inspection, credentials:* Vehicle inspection controls the legality of goods/person transportations [5]. The actions of stopping vehicles to verify the validity of the driver's license, examine vehicle or trip documentation or check the physical status of vehicles before entering a road infrastructure are typical examples of vehicle inspections.
  The wireless vehicular network allows digital service exchange between vehicles and road infrastructures and makes available a large set of significant vehicle data (e.g., engine status, tire pressure, cargo documents) directly to the infrastructure information system applications.
- *Cargo monitoring and tracking:* Wireless access for vehicular environment fills the gap for seamless and continuous tracking at the cargo-level for transit from indoors to outdoors and from warehouses to containers. Vehicular network will develop a tracking system which supports continuous and ubiquitous cargo-level monitoring.

2.1.4 Traffic Management Applications

Highway congestion is imposing an intolerable burden on drivers. Because congestion occurs when the demand for travel exceeds highway capacity, a sound approach to reducing congestion will involve a mix of policies affecting demand and capacity depending on local circumstances and priorities [6,7]. One of these policies is to apply traffic management applications. Traffic management applications offer diverse services among others [8]: *Traffic management centre, Electronic toll collection system* and *Smart traffic signals*.

- *Traffic Management centre:* is used in the Intelligent Transportation System in order to guide vehicular traffic. It offers the following services:
  - Traffic reporting that advise road users.
  - Navigation systems that help drivers locating optimal routes, hotels, restaurants, etc. These services are location-based and display information based on vehicle geographic location.
  - Traffic counters that provide real-time traffic counts.
  - Convergence indexing road traffic monitoring that provides information on the use of highway on-ramps.
  - Parking guidance and information systems that offer dynamic advice to motorists about free parking.
- *Electronic Toll Collection System (ETC):* ETC system has been seen as an effective way to finance new infrastructure and improve traffic flow. ETC can also save road travellers time and frustration, allowing them to drive non-stop through tolling area.
- *Smart Traffic signals:* The application of a distributed control system to traffic management is called "Smart Signals" [9]. It is based on spatially distributed microprocessors connected by Ethernet. The microprocessors communicate complex data to the traffic controller. The system responds to individual needs of people and vehicles for improved quality of service.

2.2 Safety-Related Applications

The most pressing applications for vehicular networks pertain to safety features and should be offered on all vehicles. Safety-related applications usually demand direct communication due to their delay-critical nature. One such application would be emergency notifications, e.g. emergency braking alarms. In case of an accident (the airbag trigger event) or sudden hard breaking, a notification is sent to the following cars. That information could also be propagated by cars driving in the opposite direction and, thereby, conveyed to the vehicles that might run into the accident.

Safety-related applications may be grouped in three main classes: information, assistance, and warning.

2.2.1 Information Applications

Driver applications provide information about the vehicle's surrounding environment and the vehicle itself, using internal and external sources. The information propagated to the road drivers help them to adapt to current road conditions. One such application could be the dissemination of information related to speed limit or work zone information.

2.2.2 Assistance Applications

These applications provide cooperative driver and lane-changing services.

- An advanced assistance service is *cooperative driver assistance system*, which exploits the exchange of sensor data or other status information among cars.
- *Lane Change Assistance (LCA):* This application assists the driver in choosing the optimum instant for lane change and influences the drivers' behaviour towards improving overtaking manoeuvre [10].

2.2.3 Warning Applications

Warning applications provide information about future hazardous road conditions, obstacles, erratic drivers, and prioritised vehicles (emergency vehicles). The basic idea is to broaden the range of perception of the driver beyond his (her) field of vision and further on to assist the driver with autonomous assistance applications. Several services are offered within this category, among others:

- *Intersection collision warning:* To avoid intersection collisions, necessary information of the intersection vicinity needs to be provided to drivers beforehand [11–14]. When approaching or crossing intersections, a driver should be informed of imminent collisions due to inattention, faulty perception, obstructed views or intoxication. These types of systems consist of vehicles continually relaying information to a beacon located in the approaching intersection.
- *Forward Collision Warning (FCW):* Forward Collision Warning systems detect an imminent crash, may warn the driver and automatically apply partial or full braking to minimize the crash severity.
- *Electronic Emergency Brake Light (EEBL)*: Emergency Electronic Brake Light enhances the driver visibility by disseminating the warning messages through the wireless links among vehicles [15].

2.3 Vehicular Application Requirements

Vehicular applications have different requirements due to their different characteristics. These requirements are related to connectivity, reach, mode, data size/connection duration, service delivery, security and privacy as exhibited in Table 1.

Table 1 Vehicular applications requirements

Application types	Safety applications	Non-safety: entertainment
Connectivity	Always-on	On-demand/ transaction
Reach	Local	Distant
Mode	Geocast/multicast	Unicast/multicast
Data size/connection duration	Small/short	Large/various
Service delivery	All neighbours/ some	Location-aware/wide-area
Security	Required	Required
Privacy	Required	Required

Depending on application types, safety and non-safety applications require either V2V or V2I communications.

Most of safety applications rely on vehicles in order to disseminate critical information. Therefore, they are mainly based on V2V communications. It is noteworthy that information and intersection collision warning necessitate having a road side unit that relays and exchanges information to vehicles. Therefore, a V2I communication is envisioned for these application types.

The majority of non-safety applications rely on infrastructure in order to have a wide area connection. Therefore, they are based on V2I communications. It is worth mentioning that sharing and some entertainment applications (Peer-to-Peer) applications are based on V2V communications.

Recently, WiMAX is emerging as one of the possible candidates for Vehicle to Infrastructure communications. Consequently, applications that rely on V2I communications should be carried by WiMAX classes of service. Next, we will investigate our WiMAX classes of services mapping proposal.

3 WiMAX MAC Quality of Service

3.1 WiMAX Classes of Service

After Subscriber Station (SS) registration, connections are associated with the service flow which defines the quality of service parameters for the Protocol Data Units (PDUs) exchanged on the connection.

In order to support QoS for different traffic types, the 802.16e MAC protocol defines several bandwidth request-allocation mechanisms and five QoS classes of service that support diverse service flows: Unsolicited Grant Service (UGS), Real-Time Polling Service (rtPS), Extended Real-Time Polling Service (ertPS), Non-Real-Time Polling Service (nrtPS), and Best Effort (BE).

With UGS, the amount of allocated bandwidth is fixed, and explicit bandwidth request is not required. In the case of rtPS, the base station (BS) provides unicast request opportunities for a SS to send its request at a predefined interval. In other words, the BS periodically polls the SS to allocate the uplink (UL) bandwidth request.

ErtPS is a combination of UGS and rtPS. Unsolicited periodic grants of bandwidth are provided but with flexibility in having dynamic data rates. The SS may request changing the size of the UL allocation.

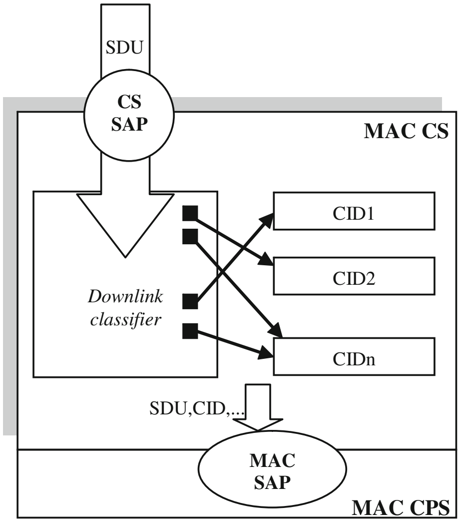

Fig. 1 MAC classification and CID mapping [2]

As for nrtPS, the BS polls the SS less frequently than in rtPS. However, SSs are allowed to use contention request opportunities to send a bandwidth request message. With BE, bandwidth messages can only be transmitted through contention request opportunities, thus the performance achieved can vary sharply.

3.2 WiMAX MAC Layer

The MAC comprises three sublayers: the security sublayer, the Common Part Sublayer (CPS) and the Service-Specific Convergence Sublayer (CS) [2]. The MAC CPS provides the core MAC functionality of system access, bandwidth allocation, connection establishment and connection maintenance.

On the other hand, the MAC CS provides any transformation or mapping of external network data, received through the CS service access point (SAP), into MAC Service Data Units (SDUs) received by the MAC CPS through the MAC SAP (Fig. 1). This includes classifying external network SDUs and associating them to the proper MAC service flow identifier (SFID) and connection identifier (CID).

Classification is the process by which a MAC SDU is mapped onto a particular connection for transmission between MAC peers. The mapping process associates a MAC SDU with a connection, which also creates an association with the service flow characteristics of that connection. This process facilitates the delivery of MAC SDUs with the appropriate QoS constraints.

3.3 WiMAX Classes of Service Mapping

Vehicular safety and non-safety applications will be carried by WiMAX technology in the V2I scenario. For that, these applications should be mapped to the appropriate classes of service.

Vehicular applications have different QoS requirements (latency, jitter, packet delivery ratio) as exhibited in Table 2.

Table 2 Vehicular applications WiMAX mapping

	Applications	Vehicular communications	Latency/Jitter	Packet delivery ratio	WiMAX class of service
Safety applications	Information	V2I	Ultra low/ultra low	High	UGS
	Assistance	V2V	Ultra low/ultra low	High	–
	Warning FCW	V2V	Ultra low/ultra low	High	–
	Warning EEBL	V2V	Ultra low/ultra low	High	–
	Intersection collision warning	V2I	Ultra low/Ultra low	High	UGS
Non-safety applications	Entertainment	V2V/V2I	Various	Various	rtPS/nrtPS
	Sharing	V2V	Medium/medium	High	–
	Cargo	V2I	Medium/medium	High	nrtPS
	Traffic management	V2I	Low/low	High	rtPS

Safety applications carry critical information and as such should have stringent quality of service parameters. Therefore, they are mapped to UGS class of service when they need V2I communication.

Entertainment applications comprise streaming, interactive and background applications. Therefore, QoS parameters are various and their WiMAX mapped class of service is rtPS for streaming and nrtPS for interactive and background.

Vehicular sharing and cargo applications require less stringent QoS parameters than other critical applications and therefore are mapped to nrtPS class of service. Traffic management applications provide real-time information and should be mapped to rtPS WiMAX class of service.

In the next sub-section, we will highlight the scheduling algorithms devoted to provide QoS for WiMAX class of services.

3.4 WiMAX Scheduling Algorithms

There have been several proposals for scheduling the above-mentioned classes of service in the literature. Some of the proposed algorithms were defined in an attempt to meet QoS requirements of classes of service, provide fairness to the users or to strike a balance between bandwidth utilization and QoS. Other algorithms rely on channel characteristics for decision making processes. We have made a study of the existing scheduling algorithms and found that they fall into three categories:

3.4.1 Simple Scheduling Algorithms

Simple scheduling algorithms are considered for all classes in order to provide QoS, flow isolation and fairness. In [16], Hawa et al. proposed a bandwidth allocation scheme that divides the service classes into three types of connections. Each type has a different scheduling scheme: first in first out (FIFO), weighted fair queuing (WFQ), and priority queue (PQ).

Some research studies propose to have a PQ scheduling: The class with the highest priority (UGS) will be served until its queue gets empty. Then, comes the turn of lower priority class.

The problem with PQ is that the lower priorities such as BE could go through bandwidth starvation whenever the highest priority flow continues for a long time.

Custom Queuing (CQ) solves the PQ problem by applying a fixed boundary scheme. Each traffic type has the same number of slots permanently allocated to it and hence encounters no competition from other types to share its resources. This policy may be inefficient in case resources are not fully utilized and hence are wasted by one traffic type while another is suffering from congestion.

In [17], authors define a dynamic allocating priority queue (DAPQ) scheduling scheme based on CQ in which each traffic type gets a portion of the resource. If an assigned bandwidth is unused, it will be allocated to another traffic type. This solution needs an efficient tuning of the bandwidth reservation percentages.

The movable boundary strategy (CMBS) overcomes this drawback by allowing a limited sharing of resources.

Non-real-time traffic can be allocated extra channels if they are not used by real time traffic but are pre-empted by the latter when it requests resources. Movable boundary strategies are found to achieve a reduction of queuing delay for real-time traffic compared to fixed boundary ones [26].

3.4.2 Cross-Layer Scheduling Algorithms

Cross-layer scheduling algorithms exploit the variability in channel conditions and modulation schemes based on SS locations.

An Opportunistic scheme is presented in [18], in which channel characteristics are used as parameters for decision making processes.

Sayenko algorithm satisfies each connection's minimal bandwidth requirement with considering adopted modulation, and then equally allocates the remaining bandwidth to each connection [19].

In [20], the authors proposed an algorithm that dynamically adjusts the downlink/uplink bandwidth ratio, satisfies connections QoS bandwidth requirements and allocates more bandwidth to the connections with better channel quality for promoting the throughput. Lack of fairness is the major drawback of this proposal. In order to resolve this problem, a downlink opportunistic fair scheduling scheme is proposed in [21]. A scheduler at the BS decides the order of downlink bursts to be transmitted. The decision is made based on the quality of the channel and the history of transmissions of each SS. It takes advantage of temporal channel fluctuations to increase the BS's throughput and maintain fairness by balancing the long term average throughput of SSs.

In [22], an opportunistic scheme is proposed for scheduling heterogeneous traffic in the downlink. The scheduler, located at the base station, uses the information of the channel and queue status of the users to schedule the traffic with different quality of service requirement and different arrival rate admitted to the queues in the base station. The scheduler deploys a differentiation technique, based on a notion of stability, to satisfy different service rate requirement of heterogeneous traffic types. This proposed solution offers prescribed delay for real-time traffic, and rate guarantees for non-real time traffic.

3.4.3 Hierarchical Scheduling Algorithms

This category combines several queuing disciplines in more than one layer. Once bandwidth has been assigned to each class using the first layer scheduling algorithms, a legacy algorithm is executed within each class in the second layer. An important aspect of algorithms in this category is the overall allocation of bandwidth among the scheduling services.

Wongthavarawat in [23] adopted a two-layer scheduling scheme where bandwidth between different service classes is allocated with strict priority in the first layer, and each service class has its own scheduling algorithm in the second layer.

Chen and Jiang individually kept the Wongthavarawat approach in the second layer. However, they modified the first layer in an attempt to solve the starvation problem caused by adopting strict priority [24,25]. In the first layer, Chen used Deficit Fair Priority Queue (DFPQ) and Jiang used leaky bucket.

In this paper, we propose a hierarchical scheduling algorithm and provide service differentiation via the Double Movable Boundary Scheme. H. Koratem and one of this paper co-author, S. Tohme, have proposed DMBS in [26] and applied it in a satellite TDMA-based systems. This strategy periodically modifies the resource allocation decision at the beginning of each frame to adapt it to the network loading conditions while always guaranteeing a minimum of resources for each traffic class at all loading conditions. The present paper proposes to implement DMBS in vehicular networks.

The key idea of this algorithm is the following: A common resource pool, the CRP, contains a number of resources which can be dynamically shared between traffic categories. The sharing process is tightly regulated to protect the relative quality of service parameters when the system is subject to congestion conditions.

Our contribution of this algorithm in vehicular networks is twofold:

- The proposed algorithm increases efficiency of bandwidth allocation without violating QoS requirements.
- The algorithm provides a service differentiation without implying a starvation for the least-priority class of service.

4 Applying DMBS in V2I Vehicular Network

4.1 Context of the DMBS Proposal

Our work considers point-to-multipoint architecture of WiMAX networks where transmission occurs between a BS and vehicles or SSs. We assume that each vehicle is equipped with a IEEE 802.16e adapter. A WiMAX base station is set-up at the road side.

All MAC transmissions are based on a connection-oriented approach. The identification of each connection together with its service flow requirements provides the MAC layer with the basic QoS, which needs to be maintained for a specific connection.

In detailing and analyzing the proposed DMBS scheme, we limit our discussion to two important vehicular applications: Traffic management and interactive (Web) applications, which will be based on V2I infrastructure.

As discussed in section III.C, traffic management and interactive (Web) applications will be mapped to rtPS and nrtPS WiMAX classes of service. Next, we will describe the MAC CPS downlink scheduler located at the road side base station.

4.2 Downlink Scheduler

Our proposed downlink scheduling algorithm works in two layers (Fig. 2). In the first layer, connections of the same class of service are scheduled using an appropriate algorithm.

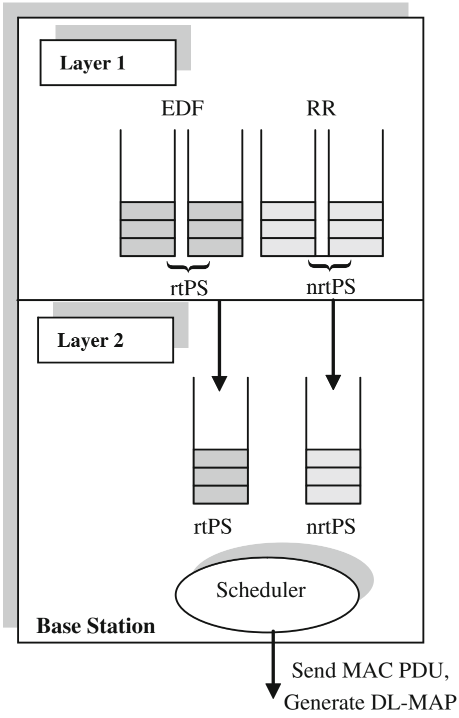

Fig. 2 MAC CPS downlink scheduler

For all connections holding rtPS traffic, the scheduler uses Earliest Deadline First (EDF), where packets with the earliest deadline will be scheduled first.

Since rtPS class of service requires stringent QoS parameters, EDF is devised for scheduling rtPS traffic. In fact, EDF is a dynamic scheduler adequate for real-time services because of delay bound properties and QoS metrics guarantees

As for nrtPS connections, the scheduler uses Round Robin (RR) queuing discipline, where each service gets a fair share of the allocated bandwidth in a RR fashion. RR is an efficient scheduling algorithm advocated for nrtPS since it assigns time slots without priority to each service flow in equal portions and in order.

In the second layer, the MAC scheduler proceeds as follows:

1 rtPS and nrtPS queues are served according to the Double Movable Boundray Scheme as described in sub-section D.
2 The BS sends the DL-MAP message in order to notifiy SSs about their bandwidth allocations. The DL-MAP contains the timetable of the downlink grants in the forthcoming downlink sub-frame as specified next.

4.3 TDD Frame Structure

In TDD-based OFDM systems, a frame is divided into two sub-frames: an uplink sub-frame and a downlink sub-frame (Fig. 3). The downlink sub-frame consists of only one downlink physical PDU (DL PHY PDU). The DL PHY PDU begins with a preamble, followed by the Frame Control Header (FCH).

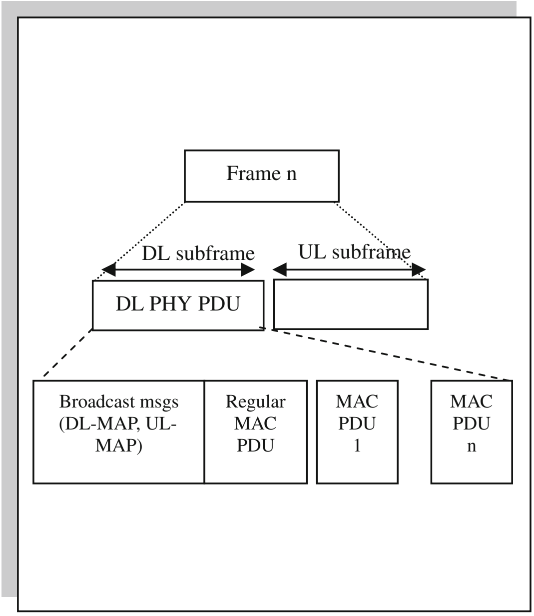

Fig. 3 MAC frame

The broadcasted DL-MAP and UL-MAP MAC management messages will be in the burst following the FCH and define the access to the downlink and uplink information respectively. The DL-MAP is a MAC management message that defines burst start times on the downlink. Equivalently, the UL-MAP, following the DL-MAP message, is a set of information that defines the entire (uplink) access for all SSs during a scheduling interval. Then, various active SSs send their data in the assigned time slots according to the scheduling algorithms as specified in next sub-section.

4.4 DMBS Model

In the work at hand, we tackle the problem of the movable boundary allocation technique taking into account the different quality of service requirements of rtPS and nrtPS traffic.

In the following, we consider that resources are the symbols offered by the WiMAX frame. Further, we suppose that a fixed number of symbols is reserved for UGS class.

In fact, we consider that safety applications such as intersection and collision warning should be assigned the highest priority, due to the urgent disseminated messages. Consequently, safety applications, mapped to UGS WiMAX applications (Table 2), should be reserved a fixed amount of unshared resources. Therefore, in the special context of vehicular networks and when applying DMBS, we can not assume that UGS compartment may be used by less-priority classes of service.

The remaining number of symbols, F, on the downlink frame is divided into three distinct parts: one part is reserved for rtPS traffic composed of a number C_1 of symbols, the second for nrtPS traffic composed of a number D of symbols and the third part constitutes a common resource pool, *CRP*, such that $CRP = F - C_1 - D$; C_1 represents the total resources available for rtPS calls at normal loading conditions to achieve a certain guaranteed blocking probability (Fig. 4).

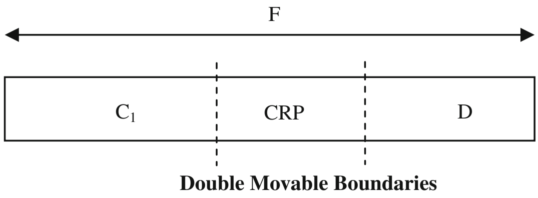

Fig. 4 DMBS mechanism

The CRP contains a number of common resources which can be dynamically shared between both traffic categories. The sharing process is tightly regulated to protect the relative quality of service parameters when the system is subject to congestion conditions. nrtPS bursts can make use of the available resources in both the CRP and the rtPS compartments when rtPS is not fully utilizing them. In addition, rtPS packets can be assigned resources from the CRP when nrtPS data queue is below a certain threshold.

Several measures of protection are however established to prevent nrtPS queues from building up when its load rises in the network. This will be explained in more details in the following sub-sections.

The DMBS allocation algorithm is initialized at the beginning of each control period and starts by examining and allocating channels to waiting rtPS packets.

- rtPS Allocation Procedure: Waiting rtPS packets will be transmitted if resources are available in the rtPS compartment. After all resources on the rtPS sub-frame are consumed and in case there are still more packets waiting to be satisfied, the scheduler proceeds as follows:
  - The scheduler checks the length of the nrtPS data queue.
  - If the latter is less than a certain pre-specified threshold, rtPS calls are granted access to some resources in the CRP sub-frame; we assume that α is the fraction of CRP allocated to rtPS traffic.
  - Conversely, if the data queue length exceeds the specified threshold, rtPS requests are denied access to the CRP sub-frame.

  They are then made to wait for the release of resources either in the rtPS sub-frame or in the CRP only when the nrtPS data queue length goes below the threshold.
  rtPS packets are dropped and they exit the system if their waiting delay exceeds the deadline.
- nrtPS Allocation Procedure: Next comes the turn for allocating resources to nrtPS traffic. Its packets are generally queued until resources are available on the frame. First bursts are allocated resources from the nrtPS sub-frame. If there are still waiting packets, the CRP and the rtPS sub-frames are searched for available channels which can then be assigned to data for the duration of the burst.
- nrtPS Queue Threshold: The nrtPS queue threshold choice has a considerable impact of the overall performance. Its value can be either permanently fixed or dynamically variable to follow the change in the network loading status.

In the first case, a certain value is specified for the queue threshold and maintained during the operational time of the scheme. In the dynamic threshold case, several techniques can be implemented to vary the threshold value during the operation of the allocation scheme. One of these is the CRP dependent technique.

The threshold is dynamically varied in each control period as a function of the number of rtPS borrowed resources from the CRP. This will provide protection to the bursty data traffic against the continuous rise of rtPS load.

$$DTQ = \frac{L_{th}.C_1}{C_1 + N} \tag{1}$$

where L_{th} is the initial threshold and N is the number of allocated CRP resources to rtPS packets.

Next, we will elaborate an analytical model of the DMBS mechanism.

5 DMBS Analytical Model

The radio channel is divided into frames as shown in Fig. 5. We will adopt a discrete time approach and monitor the state of the system at the end of a certain frame n at the instant t^-, and just before the beginning of the following frame $n+1$.

We consider the following parameters:

F = Frame duration in terms of number of symbols.

T = Frame duration time (seconds or any time unit).

C_1 = Maximum number of resources allocated to rtPS connections at high nrtPS data loads.

C_2 = Maximum number of resources that can be allocated to rtPS connections at low nrtPS data traffic loads $C_2 = C_1 + CRP$.

D = Minimum number of resources allocated to nrtPS connections under all loading conditions $D = F - C_2$

$Z_n^{rtPS}\left(resp. Z_n^{nrtPS}\right)$ = Number of rtPS (resp. nrtPS) packets transmitted within frame n.

$V_n^{rtPS}\left(resp. V_n^{nrtPS}\right)$ = Number of queued rtPS (resp. nrtPS) packets waiting for transmission at the end of frame n.

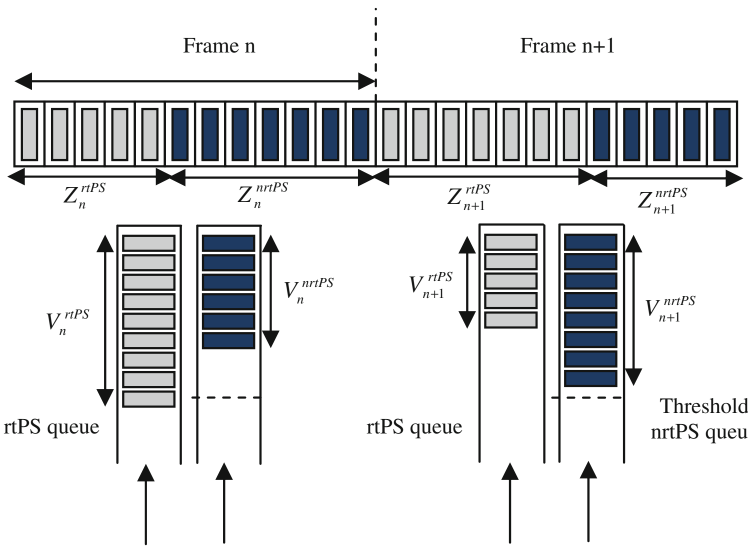

Fig. 5 DMBS analytical model

$\beta_{n+1}^{rtPS}\left(resp.\beta_{n+1}^{nrtPS}\right)$ = Number of rtPS (resp. nrtPS) packets arrivals during frame $n+1$.
L_{th} = Threshold value of the filling level of the nrtPS queue.
We set

$$P_n(x, y, z, v) = P\left(Z_n^{rtPS} = x, V_n^{rtPS} = y, Z_n^{nrtPS} = z, V_n^{nrtPS} = v\right) \tag{2}$$

where $\left(Z_n^{rtPS}, V_n^{rtPS}, Z_n^{nrtPS}, V_n^{nrtPS}\right)$ is the vector representing the state of the system at the end of frame n.

At this stage, we shall proceed with finding the functions describing the state variables at end of frame $n+1$.

The number of rtPS packets transmitted in frame $n+1$ $\left(Z_{n+1}^{rtPS}\right)$ is calculated as:

$$Z_{n+1}^{rtPS} = Inf\left(V_n^{rtPS}, C_1\right).1_{\left(V_n^{nrtPS} \geq L_{th}\right)} + Inf\left(V_n^{rtPS}, C_2\right).1_{\left(V_n^{nrtPS} < L_{th}\right)} \tag{3}$$

In terms of probability distribution, this can be written as:

$$\begin{aligned} P\left(Z_{n+1}^{rtPS} = i\right) &= P\left(Inf\left(V_n^{rtPS}, C_1\right) = i | V_n^{nrtPS} \geq L_{th}\right).P\left(V_n^{nrtPS} \geq L_{th}\right) \\ &\quad + P\left(Inf V_n^{rtPS}, C_2) = i | V_n^{nrtPS} < L_{th}\right).P\left(V_n^{nrtPS} < L_{th}\right) \end{aligned} \tag{4}$$

The number of rtPS packets in queue at the end of frame $n+1$ is computed as follows:

$$V_{n+1}^{rtPS} = V_n^{rtPS} + \beta_{n+1}^{rtPS} - Z_{n+1}^{rtPS} \tag{5}$$

We assume that rtPS packet arrivals follow a Poisson distribution with a λ_{rtPS}intensity. Hence, β_{n+1}^{rtPS} has the following distribution:

$$P\left\{\beta_{n+1}^{rtPS} = l\right\} = \frac{(\lambda_{rtPS}T)^l.\exp(-\lambda_{rtPS}T)}{l!} \tag{6}$$

Following the same reasoning for nrtPS traffic, we can write that:

$$\begin{aligned} V_{n+1}^{nrtPS} &= V_n^{nrtPS} + \beta_{n+1}^{nrtPS} - Inf\left\{F - Z_{n+1}^{rtPS}, V_n^{nrtPS}\right\} \\ &= \left[V_n^{nrtPS} - \left(F - Z_{n+1}^{rtPS}\right)\right]^+ + \beta_{n+1}^{nrtPS} \end{aligned} \tag{7}$$

where $[V]^+$ indicates the maximum value of $(0, V)$.

Considering the nrtPS packets arrival Poisson distribution with intensity λ_{nrtPS}, the probability distribution of $\beta_{n+1}^{nrtPS}$is as follows:

$$P\{\beta_{n+1}^{nrtPS} = l) = \frac{(\lambda_{nrtPS}T)^l.\exp(-\lambda_{nrtPS}T)}{l!} \tag{8}$$

The state of the system at the end of each frame can then be expressed in terms of the two variables V_{n+1}^{rtPS}, and V_{n+1}^{nrtPS}. The Kolmogorov equations governing the evolution of the allocation scheme can then be written in the form:

$$\begin{aligned} P_{n+1}(x_1, y_1) &= P\left(V_{n+1}^{rtPS} = x_1, V_{n+1}^{nrtPS} = y_1\right) \\ &= \sum_{x=0}^{\infty}\sum_{y=0}^{\infty} P\left(V_{n+1}^{rtPS} = x_1, V_{n+1}^{nrtPS} = y_1 | V_n^{rtPS} = x, V_n^{nrtPS} = y\right) \\ &\quad .P\left(V_n^{rtPS} = x, V_n^{nrtPS} = y\right) \end{aligned} \tag{9}$$

Since V_{n+1}^{rtPS} and V_{n+1}^{nrtPS} are conditionally independent random variables, Eq. (9) can be written in the form:

$$P_{n+1}(x_1, y_1) = \sum_{x=0}^{\infty}\sum_{y=0}^{\infty} P\left(V_{n+1}^{rtPS} = x_1 | V_n^{rtPS} = x, V_n^{nrtPS} = y\right) \\ .P\left(V_{n+1}^{nrtPS} = y_1 | V_n^{rtPS} = x, V_n^{nrtPS} = y\right).P_n(x, y) \tag{10}$$

Now, substituting Eqs. (5) and (7) into Eq. (10), then

$$P_{n+1}(x_1, y_1) = \sum_{x=0}^{\infty}\sum_{y=0}^{\infty} P\left(\beta_{n+1}^{rtPS} = x_{1-x} + z\right) \\ .P\left(\underset{n+1}{\overset{nrtPS}{\beta}} = y_1 - [y - (F - z)]^+\right).P_n(x, y) \tag{11}$$

With

$$z = Inf(x, C_1).1_{(}y \geq L_{th}) + Inf(x, C_2).1_{(}y < L_{th}) \tag{12}$$

6 Performance Evaluation

In order to validate our model, we conducted extensive simulation runs. We considered a 10 MHz channel bandwidth with an OFDM modulation. We adopted the 64-QAM: 3/4 and adopted a frame duration equal of 20 ms, equally divided into a uplink and downlink sub-frame of 400 OFDM symbols each.

We further assumed that a part of the sub-frame is reserved for control messages and UGS traffic. The remaining bandwidth available for rtPS and nrtPS is of 10 Mb/s (232 symbols). The DMBS parameters F, C1 and CRP are set to 29, 116 and 87 symbols. rtPS compartment provides 5 Mb/s, the CRP 3.75 Mb/s, and the nrtPS compartment 1.25 Mb/s. A maximum delay requirement of rtPS connections is fixed to 100 ms.

We computed the following performance parameters: the average offered throughput, queuing delay, queue length as well as the rtPS dropping probability.

Different scenarios, traffic models and traffic loads are considered in order to investigate the performance of DMBS in various network conditions and to draw conclusions on our proposed resource allocation. In a first step, we take into account a 2-state Markov Modulated Poisson Process Model (MMPP) for nrtPS traffic and show that MMPP model can be approximated by a Poisson Process. In a second step, we assume that rtPS (resp. nrtPS) packets arrive according to a Poisson process with an arrival rate of λ_{rtPS} (resp. λ_{nrtPS}) packets per second. Moreover, we assume that each packet fits in just one symbol.

6.1 Performance Results

In the following scenarios, we take into consideration different nrtPS loads: low (0.864 Mb/s), normal (3.456 Mb/s) and high load (5.18 Mb/s).

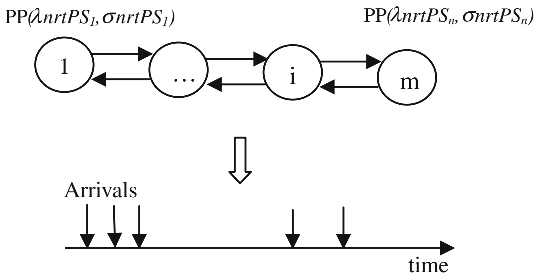

Fig. 6 MMPP model

6.1.1 Scenario 1: DMBS With Poisson and MMPP Traffic Models

In this scenario, we aim at validating the assumption of nrtPS Poisson Process (PP). Therefore, we add some burstiness and assume that nrtPS traffic is governed by a MMPP. A comparison performance analysis is elaborated afterwards.

With the MMPP model, we consider that nrtPS arrivals are generated by a source whose behavior is governed by an m-state irreducible continuous-time process which is independent of the arrival process. While the underlying modulating Markov process is spending an exponentially distributed time $\sigma nrtPS_i$ in state $i(i = 1, 2, \ldots m)$, the MMPP is said to be in a state i and arrivals are generated according to a Poisson process with rate $\lambda nrtPS$ (Fig. 6). In order to render the mathematical model tractable, we consider two states ($i = 2$) and adopt two models for nrtPS traffic as follows:

- MMPP model 1: $\lambda nrtPS_1 = 6{,}000\,\text{packet/s}, \sigma nrtPS_1 = 10\,\text{s}, \lambda nrtPS_2 = 2{,}000\,\text{packet/s}, \sigma nrtPS_2 = 10\,\text{s}$
- MMPP model 2: $\lambda nrtPS_1 = 7{,}000\,\text{packet/s}, \sigma nrtPS_1 = 1\,\text{min}, \lambda nrtPS_2 = 3{,}400\,\text{packet/s}, \sigma nrtPS_2 = 5\,\text{min}$

The small scale of time (seconds) represents variations in traffic at the terminal level, while the large (minutes) may represent variations in terms of number of active terminals joining the system during a specific period.

We conducted the simulation of DMBS with three nrtPS models: MMPP model 1 (denoted as MMPP nrtPS [1]) MMPP model 2 (denoted as MMPP nrtPS [2]) and Poisson process with $\lambda nrtPS = 4{,}000 packets/s$.

Figures 7 and 8 exhibit the offered rtPS throughput and rtPS delay. One can see that MMPP nrtPS [1] best matches the nrtPS traffic. Therefore, we can conclude that the Poisson assumption is accurate and may be matched to a MMPP small-scale variation.

6.2 Scenario 2: DMBS Dynamic Adaptation

This sub-section addresses the DMBS dynamic adaptation feature. In fact, a batch of simulation runs were conducted with different rtPS and nrtPS loads as exhibited in Figs. 9 and 10. Figure 9 shows that at high nrtPS load, rtPS traffic benefits from rtPS compartment, and thus is offered the maximum throughput of 5 Mb/s. On the other hand, at low nrtPS load, rtPS traffic can take advantage of both rtPS and CRP compartments, and thus benefits from a maximum of 8.75 Mb/s. At normal nrtPS load, rtPS traffic occupies a part of the CRP compartment, when the nrtPS filling level is below L_{th}. Thus, the mean offered rtPS throughput is comprised between 5 and 8.75 Mb/s.

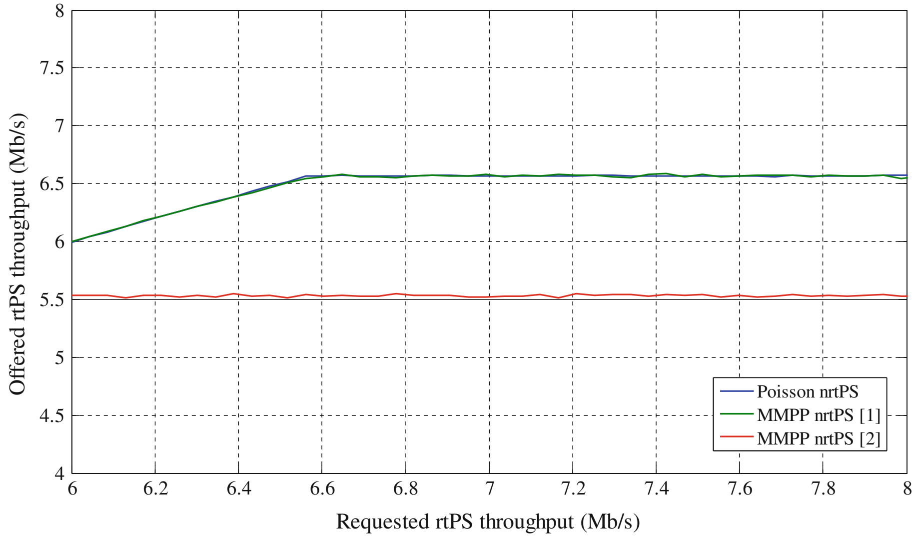

Fig. 7 Scenario 1: PS throughput with poisson and MMPP model

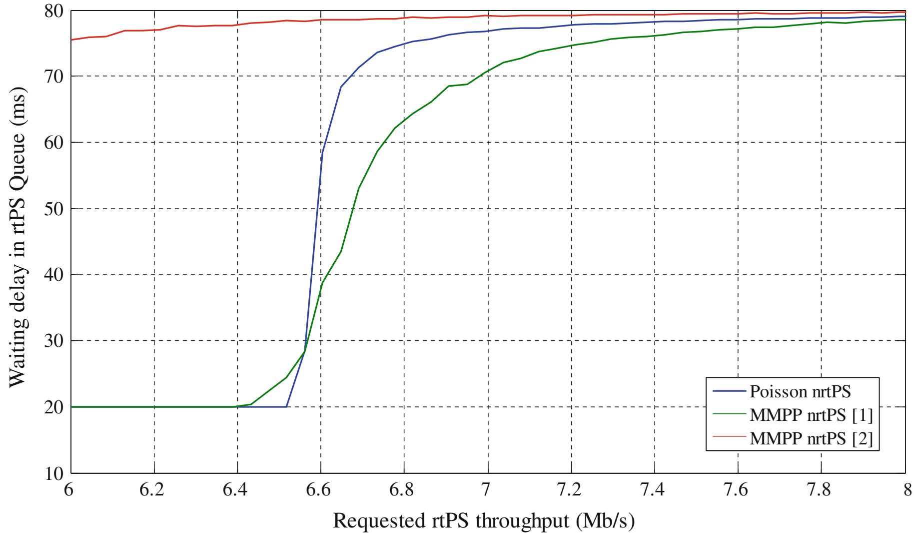

Fig. 8 Scenario 1: rtPS delay with poisson and MMPP model

Figure 10 depicts the offered nrtPS throughput as a function of the requested rtPS throughput. Since nrtPS traffic is assigned CRP compartment whenever its queue length exceeds L_{th}, offered nrtPS throughput will reach the sum of CRP (3.75) and nrtPS compartment bandwidth (1.25), i.e., 5 Mb/s.

This scenario shows the double movable boundary feature of DMBS: This feature helps in relaxing the congestion conditions of a certain traffic at asymmetrical offered loads while permanently preserving a certain minimum number of resources for each category. Bounded QoS parameters are achieved while guaranteeing a certain quality of service level for each traffic.

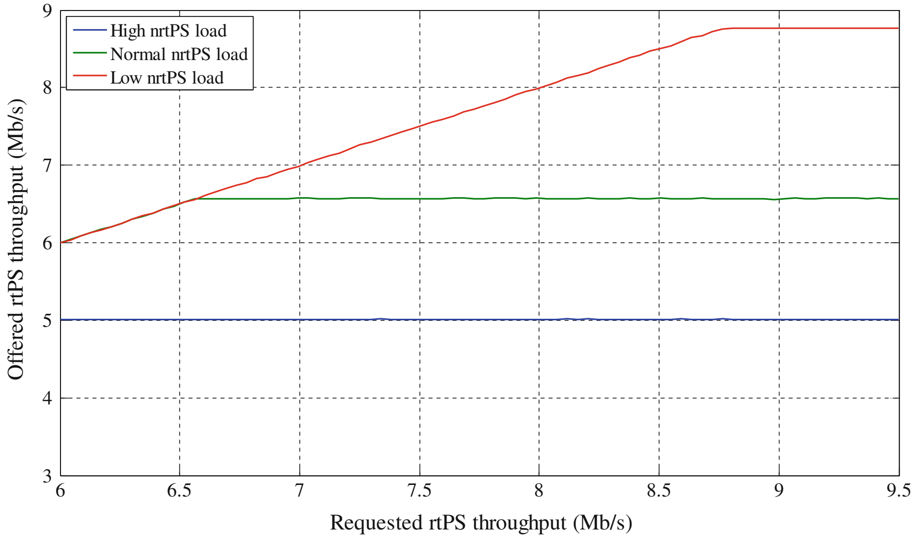

Fig. 9 Scenario 2: rtPS throughputs with different nrtPS loads

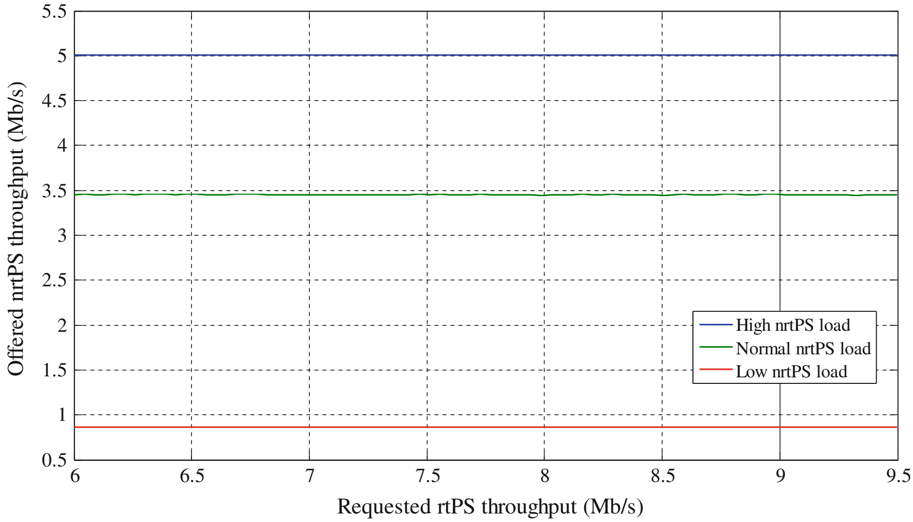

Fig. 10 Scenario 2: nrtPS throughputs with different nrtPS loads

6.3 Scenario 3: Impact of the DMBS nrtPS Queue Threshold

In this scenario, we aim at investigating the impact of the threshold L_{th} on the traffic queuing delays. rtPS (resp. nrtPS) traffic is modeled as a Poisson process with variable average throughput (resp. throughput of 3.456 Mb/s). Different DMBS thresholds are considered.

Figure 11 exhibits the rtPS average delay. One can see that when DMBS threshold gets smaller values, nrtPS is assigned higher priority to access the CRP resources and thus rtPS traffic experiences higher delays. In fact, the greater L_{th} is, the higher nrtPS queue length will be (Fig. 12), and hence the longer a packet will wait in the nrtPS queue.

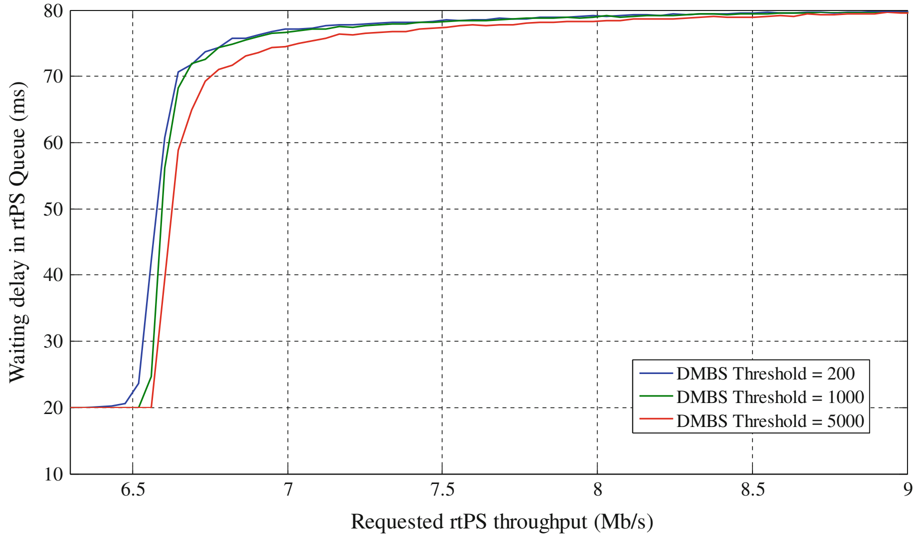

Fig. 11 Scenario 3: rtPS delay with different thresholds

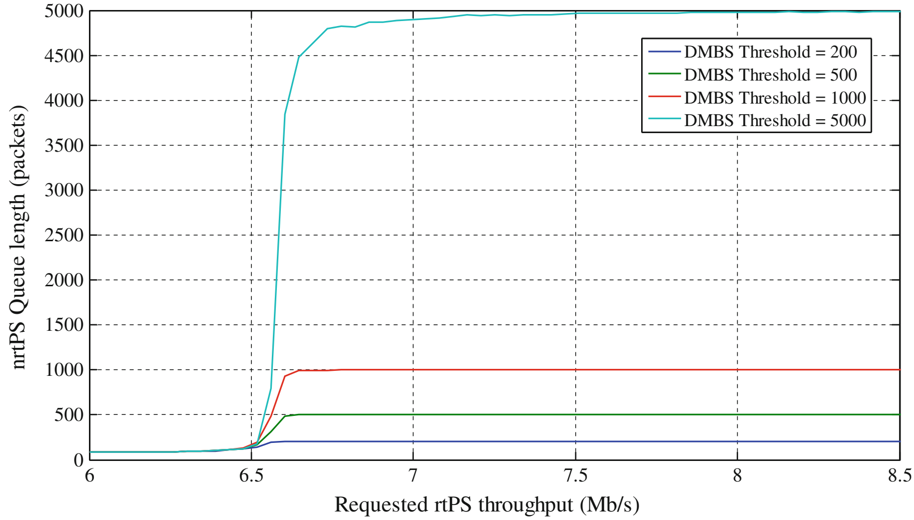

Fig. 12 Scenario3: nrtPS queue length with different thresholds

We can then conclude that high values of DMBS threshold will prioritize rtPS by reducing its queuing delay, and subsequently its dropping probability. Consequently, DMBS threshold value has a significant influence on the overall performance. Therefore, it should be carefully tuned in order to respect real-time requirements without frustrating nrtPS traffic.

It is worth mentioning that DMBS succeeds to bound the rtPS experienced delay. Consequently, there is a compromise between the maximum rtPS delay and the L_{th} value.

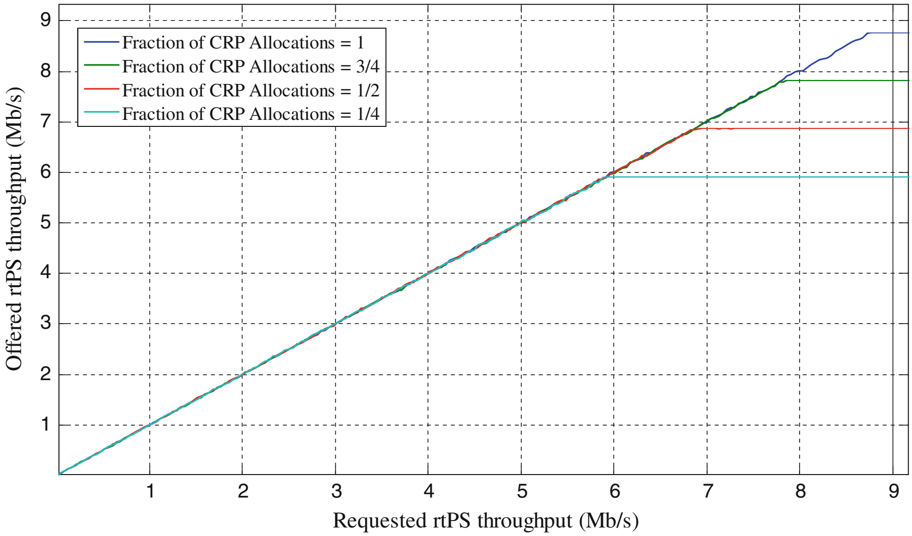

Fig. 13 Scenario 4: rtPS throughput with different CRP fractions α

6.4 Scenario 4: Impact of CRP Allocation Part

This paragraph is devoted to investigate the impact of the CRP allocation part on the overall performance. In this scenario, rtPS (resp. nrtPS) traffic is modeled as a Poisson process with variable average throughput (resp. throughput of 0.864 Mb/s). DMBS threshold is set to 300.

The part of CRP resources that may be allocated to rtPS traffic limits the maximum rtPS offered throughput. Theoretically, rtPS offered throughput may reach a maximum of $\frac{(C_1+\alpha.CRP)\times Packet\ length}{Frame\ duration}$ where α is the fraction of CRP allocated to rtPS traffic.

Since nrtPS load is low, nrtPS queue length is constantly lower than the DMBS Threshold. Consequently, rtPS traffic will benefit from the CRP resources almost all the simulation run time. This result can be identified in Fig. 13 that exhibits the variation of the offered rtPS throughput as a function of the requested rtPS throughput for different values of α.

When the requested rtPS throughput attains the maximum, the impact of the fraction of CRP allocation can be noticed. Obviously, the greater α is, the higher the maximum offered rtPS throughput is offered (Fig. 13), the smaller the rtPS queue length is and the lower the rtPS queuing delay is reached (Fig. 14).

It is worth mentioning that our DMBS mechanism succeeds to satisfy the real-time requirement of rtPS by bounding the queuing delay in all scenarios. This result is achieved at the expense of dropping packets that experience delays exceeding the deadlines (Fig. 15). One can easily notice that the rtPS dropping probability will be lower for a greater CRP fraction. Therefore, the parameter α should be carefully tuned.

6.5 Scenario 5: Comparison of DMBS With Others Algorithms

This sub-section addresses the comparison issue between DMBS, Priority Queuing (PQ) and Custom Queuing (CQ) algorithms. With PQ, the class with the highest priority (rtPS) will be served until its queue gets empty. Then, the nrtPS will have the right to be transmitted. CQ reserves a percentage of the available bandwidth for rtPS. In this context, CQ(70%)

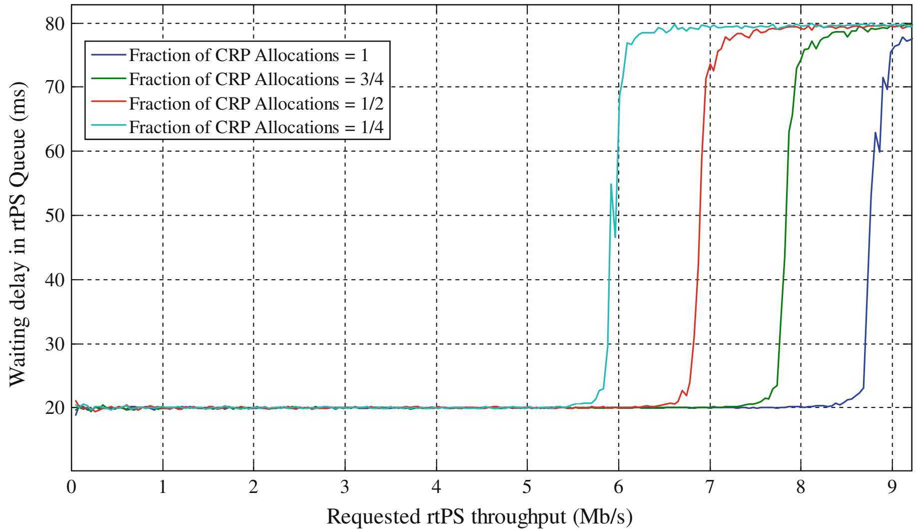

Fig. 14 Scenario 4: rtPS delay with different CRP fractions α

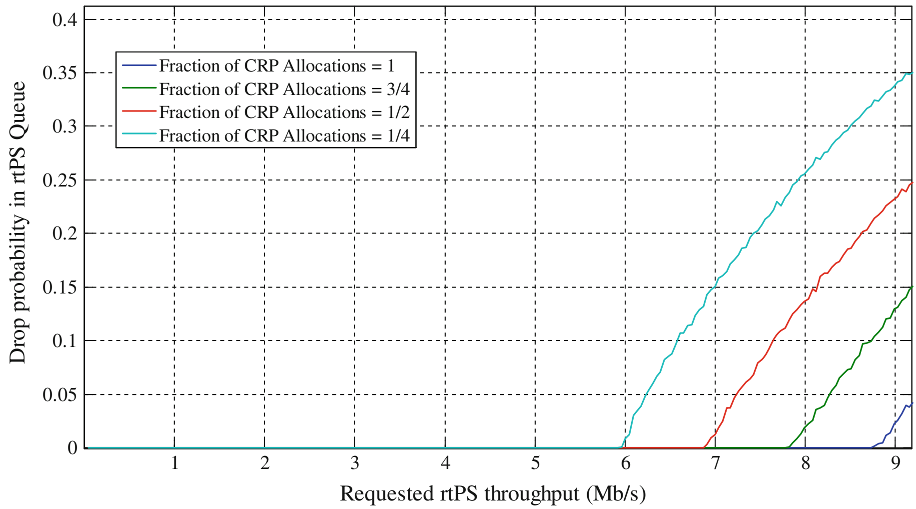

Fig. 15 Scenario 4: rtPS dropping probability with different α

and CQ(50%) represent the CQ mechanism applied respectively with 70 and 50% reserved bandwidth for rtPS traffic.

nrtPS arrivals are modeled with a Poisson process with an average requested throughput of 3.456 Mb/s (normal load). DMBS threshold is maintained fixed to 1, 000 packets, and the fraction of CRP allocations is equal to 1.

Figure 16 shows rtPS average delay with different values of rtPS loads. PQ achieves least and constant delays due to the strict priority assigned to rtPS traffic. Nevertheless, the problem with PQ is that the lowest priority traffic (nrtPS) could go through bandwidth starvation whenever the highest priority flow continues for a long time.

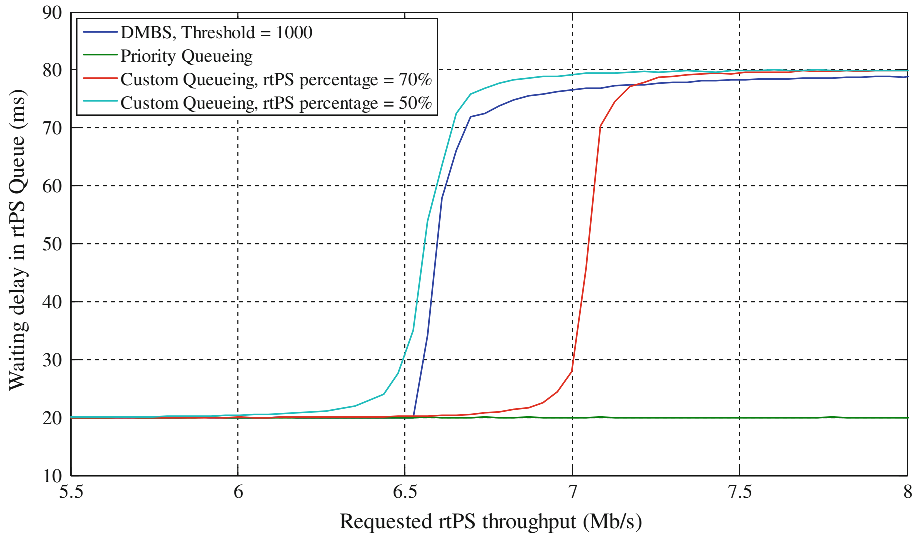

Fig. 16 Scenario 5: rtPS delay with DMBS, CQ, PQ

On the other hand, CQ (50%) implies highest delays due to the static bandwidth allocation for rtPS; this type of allocation will not be efficient for high rtPS loads.

At low rtPS loads, DMBS achieves higher delays than CQ (70%): in fact, a part of the CRP pool will be assigned to the nrtPS packets with DMBS. However, at high rtPS load, DMBS algorithm induces smaller delays than CQ (70%).

Figure 17 illustrates the average rtPS throughput. It can be noticed that PQ mechanism provides best performance for rtPS traffic as it will offer a strict guarantee for rtPS traffic. CQ (50%) and DMBS achieve rtPS throughputs less than those obtained with PQ. In fact, at normal nrtPS loads, nrtPS queue will build up will reach the DMBS threshold. This will effectively lower rtPS throughputs without degrading rtPS performance: rtPS throughput is bounded by a maximal value as highlighted in paragraph 3).

Figure 18 exhibits the nrtPS throughput. One can see that DMBS and CQ (50%) achieve a constant nrtPS throughput equal to 3.456 Mb/s. This result is expected since both algorithms are able to satisfy nrtPS requirements. On the other hand, nrtPS throughput decreases with CQ (70%) and reaches a minimum of 3 Mb/s at high rtPS traffic load. As a matter of a fact, the rtPS reserved bandwidth protects rtPS against other traffics. This policy may be inefficient in case resources are not fully utilized. On the other hand, PQ performance drastically degrades with high rtPS loads as this mechanism does not provide any guarantee for nrtPS traffic.

At this stage, we summarize performance comparison analysis at high rtPS throughput:

– Regarding the rtPS waiting average delay, DMBS achieves better delays than CQ. PQ achieves best rtPS QoS guarantees. However, it induces nrtPS degraded performance since PQ provides strict priority to rtPS.
– Regarding nrtPS average throughput, DMBS and CQ (50%) achieve best performance. PQ and CQ (70%) imply nrtPS starvation.
– As for rtPS average throughput, DMBS and CQ (50%) provides less throughputs than other algorithms. However, one can see that rtPS throughput is controlled and limited by a maximum value as highlighted before.

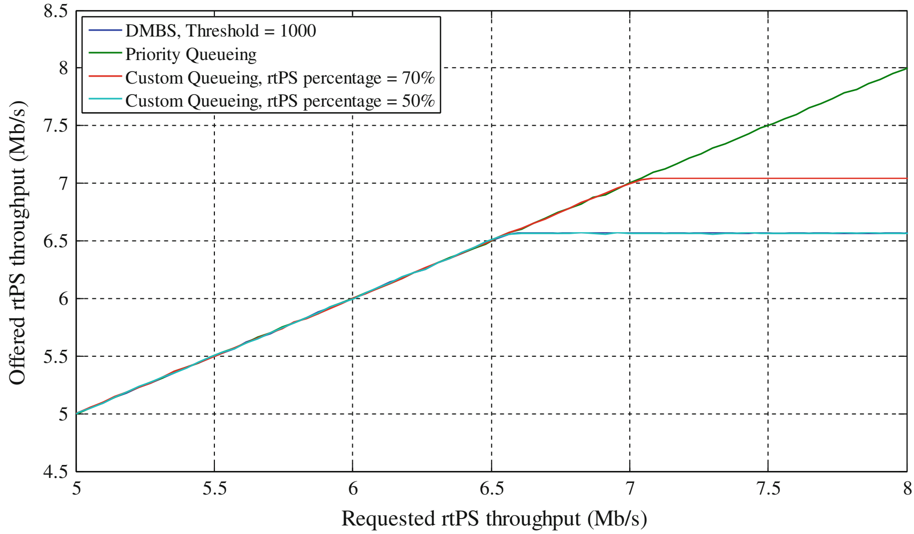

Fig. 17 Scenario 5: rtPS throughput with DMBS, CQ, PQ

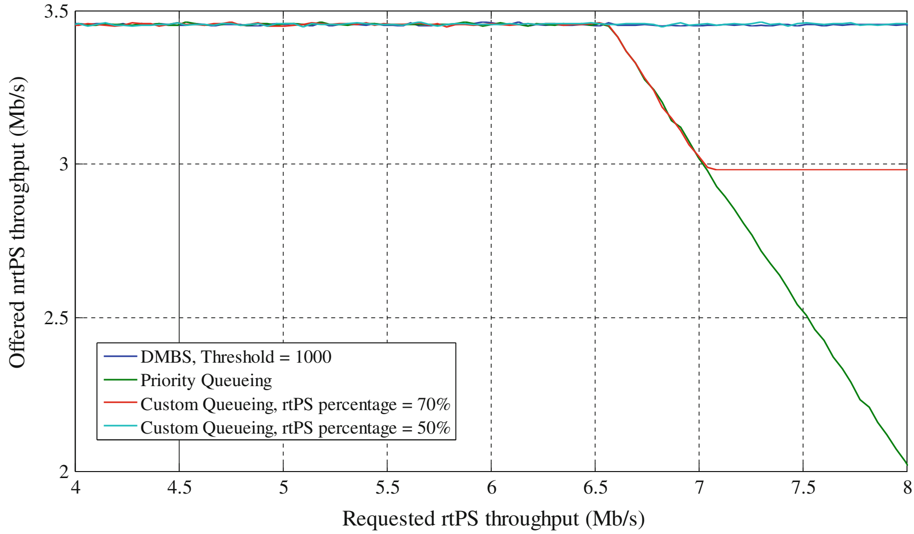

Fig. 18 Scenario 5: nrtPS throughput with DMBS, CQ, PQ

Finally, we draw the following performance analysis conclusions:

In vehicular networks, DMBS is particularly interesting since it adopts a dynamic resource allocation with a boundary moving in two directions; this feature takes into account the resource fluctuation present in wireless vehicular networks.

The real-time requirements of the vehicular traffic management application (mapped to rtPS) are respected while preventing least-priority classes (Web) from starvation problems. More specifically, traffic management (rtPS) average waiting delay as well as average throughput are bounded. On the other hand, Web (nrtPS) average throughputs do not degrade as is the case of other conventional algorithms in which each traffic type encounters no competition from other types to share its resources. Conventional policies may be inefficient in case resources are not fully utilized and hence are wasted by one traffic type while another is suffering from congestion.

7 Conclusion

In this paper, we performed a study of the Vehicular to Infrastructure communication envisioned for vehicular networks. In this context, we presented vehicular applications that will be provided to vehicular users and proposed a service class mapping in WiMAX networks. Since resource allocation and QoS provisioning are challenging tasks to achieve, we tackled the problem of MAC downlink scheduling and suggested a DMBS mechanism at the MAC CPS implemented in the WiMAX base station. DMBS periodically modifies the resource allocation decision and adapts it to the network loading conditions while guaranteeing a minimum of resources for each traffic class at all loading conditions.

When comparing DMBS to other conventionally considered resource allocation algorithms, the DMBS scheme was shown to be more efficient particularly in asymmetrical loading conditions. The efficiency is reflected in the bounded rtPS throughput, reduced delays and acceptable nrtPS QoS performance. This fact is proven by simulation models and analysis developed to evaluate the performance parameters of DMBS. We highlight the fact that DMBS offers an interesting trade-off between nrtPS starvation problem and rtPS requirements.

On the other hand, we investigated the impact of several factors on this allocation technique. These include the nrtPS queue threshold value and the fraction of the borrowed resources from the CRP. They should be well defined and dynamically tuned to reach an optimum operation.

The nrtPS queue threshold value has a considerable influence on the real-time resource allocation performance and consequently the efficiency of the DMBS policy. A low threshold favours nrtPS over rtPS traffic by reducing its waiting delay in the queue at the expense of risking a rise in the blocking probability and rtPS delay. The threshold choice depends then on the type of offered services, their relative priorities for the operator and the quality of service parameters guaranteed by the network for each traffic category. Another important factor which largely influences the performance of the DMBS policy is the number of resources allocated to rtPS calls from the CRP. Obviously, allocating a large number of CRP resources to rtPS traffic at a time can dramatically degrade the delay performance of bursty data. Together with the dynamic queue threshold value, these two factors must be properly tuned in order to protect nrtPS and rtPS traffic against large queuing delays.

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Author Biographies

Rola Naja was awarded a Ph.D. in Computer Networking at "Ecole Nationale Superieure des Telecommunications" (ENST)-Paris. Her research studies lie in the area of resource allocation and mobility handling in wireless multiservice networks. She has published several papers in International conferences and journals dealing with network modeling and performance, network adaptability and quality of service provisioning. She has chaired many sessions in International conferences. Actually, she is lecturer at ESIEE-Chamber of Commerce and Industry in Paris. She is as well researcher at PRiSM Laboratory (CNRS UMR 8114) at Versailles University.

Melhem El Helou was born in Beyrouth, Lebanon in 1986. He graduated from the Ecole Supérieure des Ingénieurs de Beyrouth, Saint-Joseph University, Lebanon, in Telecommunications and networking engineering in 2009. He received the reseach master's degree in telcommunication networks from the Saint-Joseph University and the Lebanese University in 2010. He is currently working as a teaching assistant at the Ecole Supérieure des Ingénieurs de Beyrouth, Saint-Joseph University, Lebanon, and is a Ph.D. student at the University of Rennes 1, France and the Saint-Joseph University, Lebanon (Co-supervision program). His research interests include resource allocation, WiMAX networks, heterogeneous 4G wireless networks, and RAT selection.

Samir Tohmé was born in Damascus, Syria, in 1949. He graduated from the Ecole Supérieure d'Electricité (1975), Paris, in Electrical Engineering, and received the Doctorat Degree from the Ecole Nationale Supérieure des Télécommunications ENST, Paris, in 1979. After having been with HP and SITA for five years where he worked in the distributed system field, he joined the Ecole Nationale Supérieure des Télécommunications in 1984 where he was appointed Head of the Networks Department between 1988 and 1998. He joined the University of Versailles in 2003 where he is presently Director of PRISM Laboratory. Author of one hundred and twenty five published research papers, his main research activities concern mobile and satellite networks, high speed networks and traffic control. Professor Tohmé is an IEEE senior member.