A Cross-Layer Approach to Dynamic Bandwidth Allocation in Satellite Networks

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Abstract. This work presents an innovative cross-layer approach to dynamic bandwidth allocation (BoD) in Satellite DVB-RCS networks. The algorithm is based on the assumption that, by managing the traffic at IP level through interaction with MAC level, a meaningful reduction in packet loss can be achieved, thus resulting in better resource exploitation. The proposed mechanism has been embedded in a consolidated control scheme for dynamic bandwidth allocation ([23], [1]). The interaction consists in the computation of the exact amount of MAC cells to send to the air interface during the next frame; based on this computation, the proper number of IP packets are segmented, transmitted to the MAC layer and queued in the MAC buffers. In this way, a twofold result is obtained: 1) no duplication of the scheduling function, scheduling can be performed at IP layer only, and 2) avoidance of overflows of MAC buffers. Simulations results, obtained by Opnet®, confirm the effectiveness of the proposed approach.

Keywords: Cross-layer, Bandwidth on demand, DVB-RCS Satellite Network.

1 Introduction

Traditional design paradigm in communication network, and all the more so in satellite networks, is based on the separation of different layers and the optimization of distinct parts, in order to reduce the complexity and the effort of the initial design; the interaction and interoperability among different layers and various equipments from diverse manufacturers will be obtained through the use of standardized interfaces. However in a complex system (such as a satellite network), there exists strict interdependence among layers, so the above mentioned design paradigm with tight modularity and layer independence may lead to sub-optimal or non-optimal performances and this means a non-efficient resources exploitation. The need of information exchange is evident if we consider, for example, the transport layer protocols, that require to take into account the problem of propagation delays, link impairments and bandwidth asymmetry; moreover if we consider that error correction schemes are implemented both at physical, link and (in some cases) transport layers, inefficiencies and redundancies given by a classic approach are immediate. In order to overcome these obstacles, it is necessary to explore a

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new design paradigm that propose innovative protocol architectures that violate the reference layered architecture, for example, by allowing direct communication between protocols at non-adjacent layers or sharing state variables between layers to obtain performance gains. This "violation" is known as "cross-layer design".

The cross layer approach described in this work continues a previous work ([23]) on Bandwidth on Demand procedure. The satellite control structure that computes the satellite terminal bandwidth request described in [23] hasn't got any control on packet flows from IP level to MAC level. We extend the work in [23] by introducing a disabling signal from MAC layer to IP layer, the so called "back-pressure signal", that prevent the transmission of packets to the MAC layer, if MAC buffer queues reach a defined threshold (congestion state). In this way, MAC layer functionality is kept as simple as possible: during the congestion, packet dropping (if needed) is performed at the IP layer; at the end of the congestion state, the IP level scheduler select the IP packets with the most stringent delay requirements.

The work is structured as follows: in Section 2, the problem of cross-layer as reported in literature is introduced, Sections 3 and 4 describe the system architecture and the BoD control scheme presented in [23], whereas section 5 describes the cross-layer mechanism and theoretical approach to compute the threshold level. The paper ends with a description of the system implementation and a discussion on simulation results.

2 Layers Interactions in Satellite Networks

According to recent studies carried out in [19], since satellite network scenario is moving towards a full IP integration, cross-layer is particularly significant to overcome some architectural problems. They are, for example, TCP erroneous inference of congestion state (the absence of an ACK is also due to wireless channel degradation); resources wasting while allocating bandwidth to users with very bad channel conditions; the necessity of intra and inter satellite handover and consequent rerouting that could bring to connection dropping; packet losses due to buffer overflows in real time streaming during congestion situations or particular bad wireless conditions.

In spite of this, it is worthwhile mentioning some recent works in literature to describe the progress reached in cross-layer design (in general) and in satellite networks (in particular). Most of them are related to scheduling techniques and design. For example in [3], the scheduling at the data link layer divides the traffic in two categories and applies a weighted policy mechanism to respect the QoS constraints, while at the physical layer users adapt their modulation and coding according to traffic conditions with the help of a perfect estimation of wireless channel conditions obtained by prediction-based algorithm.

In [20], QoS guarantees for CDMA networks are provided by means of cross-layer optimization across the physical and network layer. At the physical layer, the QoS requirements are specified in terms of a target signal-to-interference ratio (SIR) requirement, and optimal target powers are dynamically adjusted according to the current number of users in the system. At the network layer, both the blocking probabilities as well as call connection delay constraints are considered.

A packet scheduling algorithm in satellite digital multimedia broadcasting system is developed in [8], namely "combined delay and rate differentiation" (CDRC); this algorithm takes into account QoS parameters to prioritise different contents among different services in a dynamic environment. Moreover, in [9] the application and transport layers exchange information about QoS requirements together with MAC layer that adapts its packet scheduling decision in order to achieve QoS targets, while respecting the power constraints given by the lower layers.

In [10], an innovative allocation algorithm is presented, based on cross-layer interaction between TCP and MAC layers; it aims at synchronizing the requests of resources with the TCP transmission window trend, thus reducing delays and increasing air interface utilization; this is also the case of [11], where a new technique called "ACK compaction" is discussed to overcome the physical delay problems that leads to a sub-optimal behaviour of TCP protocol.

In [12] two different methodologies are presented: a reservation-based medium access control scheme, which uses cross-layer interaction with the physical layer to measure channel condition and predict performances through a Markov chain formulation (dynamic cross-layer), and a Neyman-Pearson MAC design optimization (static cross-layer). These two techniques, coupled to physical measures, aim at predicting optimal decision for traffic management.

The innovation proposed in this paper consists in the introduction of a cross-layer mechanism between MAC layer and IP layer, aiming at reducing expensive packet losses in the air interface; this interaction is obtained by means of a control signal that enable-disable the packet flow from IP to MAC level, according to congestion conditions.

3 System Architecture and Control Scheme

The Scenario considered in this work (see Fig. 1) consists of a DVB-RCS (ETSI 2003) geostationary satellite network with on board switching capabilities, Satellite Terminals (STs) provide Local Area Network with the access to the network, Gateways (GW) connect the satellite network to the core network (i.e. to the Internet) and a Network Control Centre located on earth that manages the satellite network resources. The NCC is in charge to prevent collisions between packets transmitted by different STs through a dynamic bandwidth assignment procedure. Each ST computes the bandwidth request and sends it to the NCC; after a period of latency, the NCC communicates the bandwidth assigned to the STs. Due to the latency of the satellite network, the traffic is being divided into two main classes: high-priority service class and low-priority service class.

The high-priority service classes require a static bandwidth assignment, due to the excessive latency of the BoD request assignment cycle. In the case of low priority classes it is possible to assign the bandwidth in a dynamic way.

The corresponding network model is depicted in Fig. 2. In DVB-RCS satellite networks, each ST has a periodic opportunity to send bandwidth requests; thus, the network model is a discrete-time system with sampling time T_C equal to the time period between two consecutive bandwidth requests (*control time*).

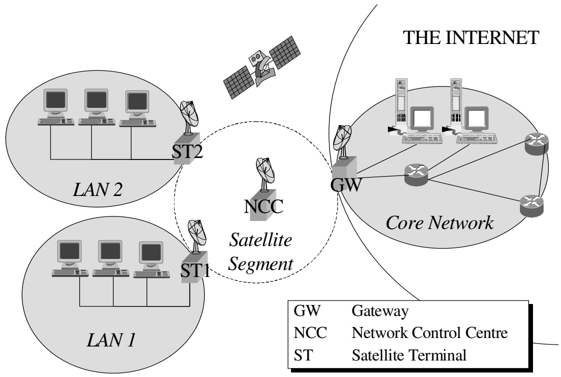

Fig. 1. Satellite reference scenario

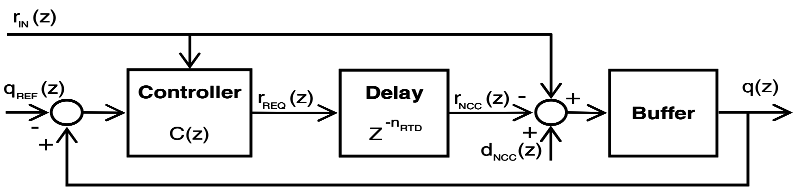

Fig. 2. Control scheme of the Satellite Network Model

The system model consists of 4 elements:

- ***Source Traffic.*** It is the traffic received by each ST during the *kth* time interval and it is modeled by an input bit rate, $r_{IN}(k)$, which is non-negative and limited by a maximum rate, r_{MAX} :

$$0 \leq r_{IN}(k) \leq r_{MAX} \tag{1}$$

- ***ST MAC Buffer.*** It collects the MAC cells waiting for transmission in the uplink and it is modeled by an integrator. Let $q(k)$ denote the queue length in this buffer at time $t = kT_C$: the variation of $q(k)$ is given by the input rate $r_{IN}(k)$ minus the transmission rate assigned by the NCC, $r_{NCC}[k]$. The following equations hold:

$$q'(k) = q(k-1) + T_C \cdot r_{IN}(k) - T_C \cdot r_{NCC}(k-1) \tag{2}$$

$$q(k) = \sigma(q'(k)) \tag{3}$$

where $\sigma(x)$ is a saturation function such that $\sigma(x) = x$ if $x \geq 0$, $\sigma(x) = 0$ otherwise.

- ***Satellite Network Delay and NCC.*** In geostationary satellite networks, the STs and the NCC communicate via the satellite; the time interval between the transmissions of a bandwidth request by the ST and the associated bandwidth allocation is fixed and equal to about 600ms (considering physical and MAC layer delays). This interval constitutes the feedback delay of the system and will be referred to as *round trip delay*. The NCC assigns the bandwidth on the basis of the requests and of the available link bandwidth: if the network is not congested, the assigned bit rate $r_{NCC}(k)$ is equal to the requested one: $r_{NCC}(k)=r_{REQ}(k - n_{RTD})$, where n_{RTD} is the *round trip delay* expressed in number of sampling periods. For the sake of simplicity, in this paper n_{RTD} is considered equal to an integer number of T_C[1]. Conversely, if the network is congested, the NCC assigns less bandwidth according to a predefined fairness policy: $r_{NCC}(k) < r_{REQ}(k - n_{RTD})$. Thus, the transmission delay and the NCC can be modeled as a delay block cascaded to an additive disturbance $d_{NCC}(k)$, defined as follows:

$$d_{NCC}(k) = r_{REQ}(k - n_{RTD}) - r_{NCC}(k) \tag{4}$$

The use of the additive disturbance models the state of the network as follows:

$$\begin{cases} d_{NCC}(k) = 0 & \text{if the network is not congested} \\ d_{NCC}(k) > 0 & \text{if the network is congested} \end{cases} \tag{5}$$

To compute the unused assigned bandwidth, has been introduced the wasted rate parameter, defined as follows:

$$r_w(k) = \sigma(-\frac{q'(k)}{T_c}) \tag{6}$$

Thus, $r_w(k)$ is null if the link utilization is achieved and positive otherwise.

With reference to the developed model, the targets of the BoD protocol can be expressed as follows:

1. The *wasted bit rate* should be null, i.e., $r_W(k) = 0$, which means that bandwidth is not wasted (*Full Link Utilization*).
2. When no congestion is occurring, $q(k)$ should be as small as possible.
3. In case of congestion, $q(k)$ grows regardless of the request policy; the objective, in this case, is that the system should recover the normal behavior when the congestion ends (*congestion recovery*).

- ***BoD Controller.*** The BoD Controller C(z) is situated in the ST and it computes the rate requested based on the input rate fed the network and on the MAC buffer measurement.

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[1] Generally, this is not true and $n_{RTD}=n+\varepsilon$, where n is an integer number and ε is a real number between 0 and 1; in this case, the generic quantity $x(k - n_{RTD})$ is computed as follows: $x(\mathrm{k} - n_{RTD}) = (1-\varepsilon)\cdot x(k-n) + \varepsilon \cdot x(k-n-1)$.

4 Dynamic Capacity Assignment

The structure of the BoD scheme was already presented in [21], and is detailed in Fig. 3: the bandwidth requests $r_{REQ}(k)$ is computed as the sum of two parts: rate-based and queue-based:

$$\begin{aligned} r_{REQ}(k) &= r_{IN}(k) + r_Q(k) = \\ &= r_{IN}(k) + Z^{-1}\{K(z)[q_{REF}(z) - q(z)]\} \end{aligned} \tag{7}$$

The expression of the queue based part is given by:

$$r_Q(k) = \frac{1}{T_C}\left(q(k) - q_{REF}(k) - T_C \sum_{i=1}^{n_{RTD}} r_Q(k-i) \right) \tag{8}$$

Where $q_{REF}(k)$ is given by:

$$q_{REF}(k) = T_C \sum_{i=0}^{T_{RTD}} r_{IN}(k-i) \tag{9}$$

In [23] and [22], a parameter $\alpha \in [0, 1]$ is introduced to regulate the ‘aggressiveness’ of the request policy. In particular, the reference queue is computed as follows:

$$q_{REF}(k) = \alpha T_C \sum_{i=0}^{T_{RTD}} r_{IN}(k-i) \tag{10}$$

and, consequently, the request is computed as follows:

$$r_{REQ}(k) = \left(\frac{1}{T_C} q\ (k) - \sum_{i=1}^{n_{RTD}} r_{REQ}(k-i) + (1-\alpha) \sum_{i=0}^{n_{RTD}} r_{IN}(k-i) \right) \tag{11}$$

By setting $\alpha = 1$, the same request policy of [21] is obtained, guaranteeing the full link utilization; by decreasing the value of α, a more aggressive request policy is obtained, which achieves lower queuing delays at the price of some bandwidth waste.

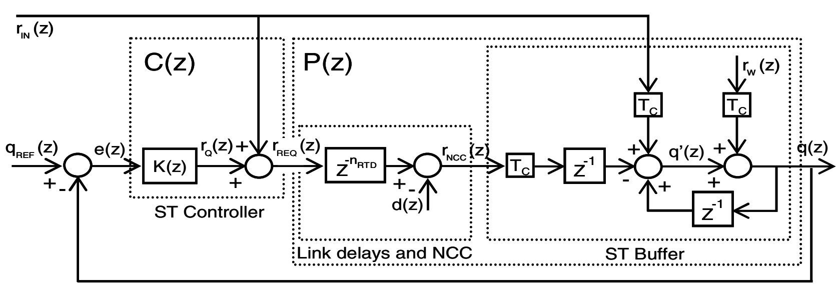

Fig. 3. System reference scheme

Finally, in [23], a Multi Model Reference Control approach has been chosen to set dynamically the value of α, in order to achieve the full link utilization when the network is congested (and thus the bandwidth is a precious resource which must not be wasted), and favor better performance in terms of queuing delays (by lowering α) as the network load decreases.

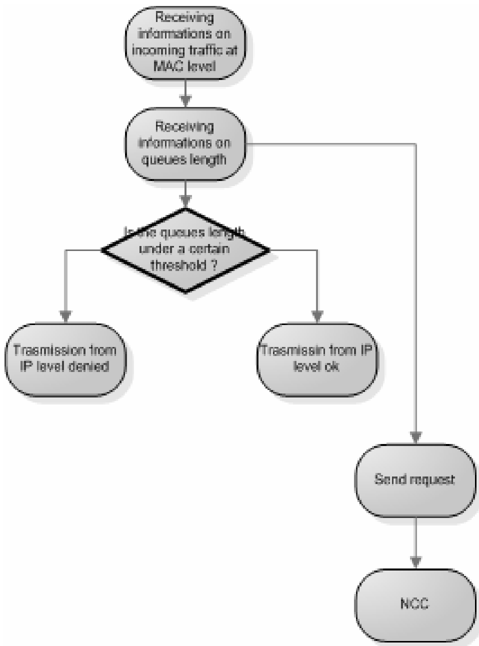

Fig. 4. Back Pressure Functional Diagram

The proposed back-pressure algorithm is based on the request computed according to the BoD algorithm of equation (9'''). The objective is to compute the dynamic threshold value $q^*(k)$ which represents the maximum number of MAX cells which should be stored in the MAC buffer. If the threshold is exceeded, the IP scheduler is blocked, and no MAC cell enters the MAC buffer until the queue length is below the threshold again (in this respect, note that the IP packets which are transmitted from the IP to the MAC layer are segmented in a given number of MAC cells; thus, it is likely that, when the IP scheduler is blocked by the back pressure-algorithm, the MAC queue length exceeds $q^*(k)$).

At time k, from (1), (2), (3) and (11) it is possible to calculate the worst-case queue length as follows:

$$\hat{q}(k+1) = T_C r_{\max} + T_C \sum_{i=1}^{n_{RTD}} r_{REQ}(k-i) + (1-\alpha) T_C \sum_{i=1}^{n_{RTD}} r_{IN}(k-i) \quad (12)$$

where n_{RTD} is the number of control time in a round trip delay. This queue length is achieved if the MAC buffer is fed with the maximum allowed rate r_{MAX}, during the current round tripe time and represent the maximum amount of packet that could be sent to the air interface.

For comparison purposes, we also developed a ‘static’ approach, which computes a fixed threshold. This static approach is also more easily implemented, since it does not require measures of the MAC cells entering the MAC buffer. The static threshold is straightforwardly computed from the control system equations via theoretical considerations. Control system theory, which was used to develop the BoD algorithm, provides the Final Value Theorem, which states that the stationary value achieved by the system can be computed as follows:

$$\lim_{t\to\infty} y(t) = \lim_{z\to 1}\left[(z-1)y(z)\right] \tag{13}$$

where $y(t)$ is the system output and $y(z)$ is its **Z**-tranform.

In our system, the output is the queue length $q(k)$, the input is the reference queue length $q_{REF}(k)$ given by equation (10); the transfer function between $q_{REF}(k)$ and $q(k)$ is immediate (see [23] for detailed demonstration):

The static threshold is then calculated in the worst-case (i.e., for $\alpha = 1$) as in the following equation:

$$\lim_{z\to 1}\frac{r_{\max}}{1-z}\left\{\frac{q(z)}{r_{IN}(z)}+\frac{q(z)}{q_{ref}(z)}\frac{q_{ref}(z)}{r_{IN}(z)}\right\}=(1+n_{RTD})T_c r_{\max} \tag{14}$$

where $r_{IN}(t)$ is set equal to the maximum rate available for on-demand traffic r_{MAX}. Note that equation (14) is also obtained by computing the worst-case dynamic threshold, i.e., by computing eq. (15) with $\alpha = 1$ and by considering that the request was the maximum allowed during the last round trip delay, i.e., $r_{REQ}(k - i) = r_{MAX}$, $i = 1,\ldots,n_{RTD}$:

$$q^*_{MAX}(k+1;\alpha=1) = T_C r_{MAX} + T_C\sum_{i=0}^{n_{RTD}} r_{MAX} = T_C(1+n_{RTD})r_{MAX} \tag{15}$$

5 System Implementation

The simulations of the proposed approach were developed using the OPNET® Modeler 11.5A PL3 (Build 3408) tool by OPNET® Technologies.

The implementation of the thresholds computed via the control theory has been implemented in the Scheduler module at IP level and in the DAMA_Agent module at MAC Level (Fig. 5).

The DAMA Agent is in charge of measuring the queue size at MAC level and of comparing this value to a threshold. Every T_C=*96ms* time interval the DAMA Agent computes the gap between the threshold and the real value of the MAC queues size and sends it with a proper signaling message to the scheduler. The scheduler receives the message and extracts the value of the threshold. Then, it is in charge of sending to the lower layer the proper amount of bits (to avoid the overflow of the MAC queues). When congestion occurs, the DAMA Agent computes a negative value of the bit to send from the IP level to the MAC level so a disabling signal is generated and the transmission is denied.

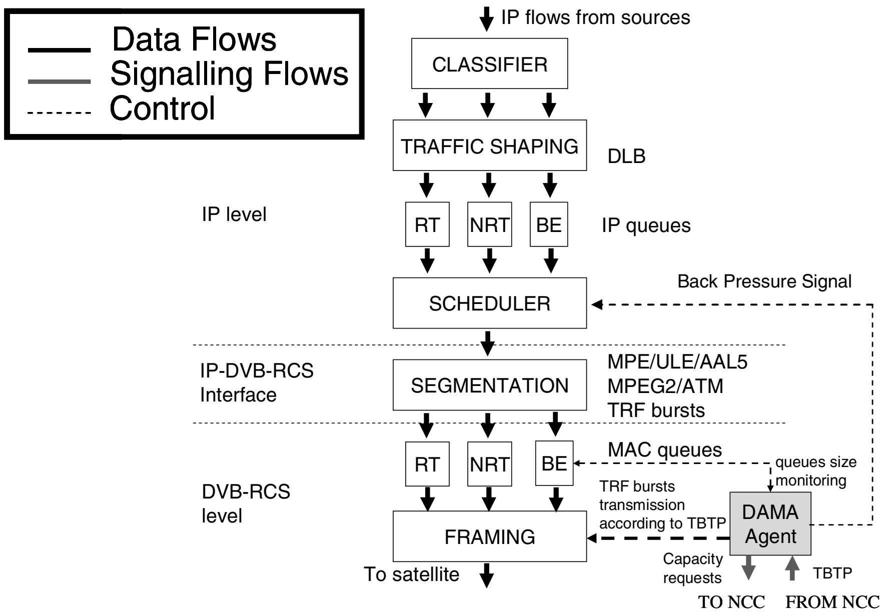

Fig. 5. Satellite Terminal system architecture

6 Simulation Results

Two simulation sets has been performed:

Simulation Set A) The system runs under no threshold at MAC level;
Simulation Set B) The system runs under a back-pressure algorithm;
The simulation parameters are shown in the following tables.

Table 1. Simulation Parameters: High Priority Traffic

	Voice	Video
Interarrival Time [s]	Constant (0.02)	Uniform (0.008, 0.01)
Packet Size [bits]	Constant (1280)	Normal (1150, 450)

Table 2. Simulation Parameters: Low Priority Traffic

	Multimedia Streaming	Data
Interarrival Time [s]	Uniform (0.0005, 0.00265)	Exponential (0.2)
Packet Size [bits]	Poisson (10800)	Pareto (6000, 1.5)

Table 3. Opnet simulation parameters

Simulation #	3
Simulation Length [sec]	450
Terminal Satellite (STs)	7
Estimated Load [Mbit]	45
Sampling Time [msec]	0.069632

Table 4. Simulation parameters high priority traffic

	Max Delay
High priority Traffic [s]	0.15
Low priority Traffic [s]	2
Best Effort Traffic [s]	5

6.1 Simulation Set A

The first simulation set shows the results obtained when no threshold is computed. The result shows that the MAC queuing delay reaches the maximum tolerated delays for both high- and low-priority MAC queues, entailing MAC layer cell dropping.

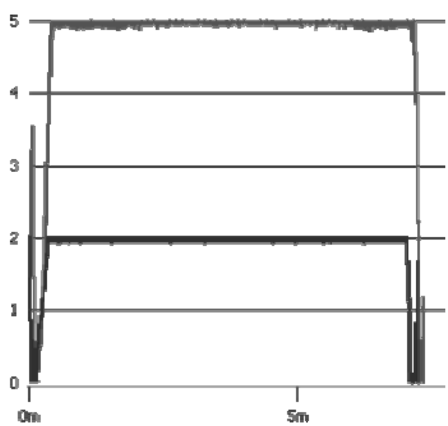

Fig. 6. Best Effort (black line) and Low priority (grey line) MAC Queuing delay

6.2 Simulation Set B

The second simulation set evaluates the performance in terms of delay for both the static and dynamic threshold approaches. With a static approach the number of packet losses at MAC level is reduced with respect to the original control scheme, because only the exact amount of packet is sent to the lower layer and can be transmitted; however the delay is still considerable and almost constant (the threshold is static!).

By using a dynamic approach the system is able to adapt to traffic condition thus minimizing better the delay of packets waiting in the MAC queues and reducing as well the packet losses.

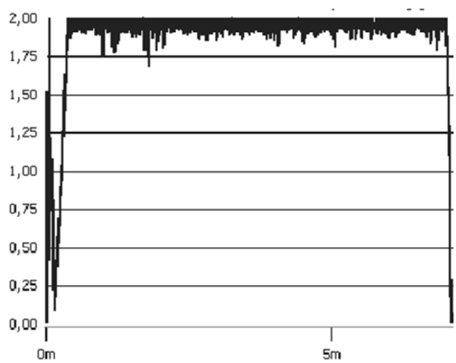

Fig. 7. IP queuing delay high priority traffic (STATIC APPROACH)

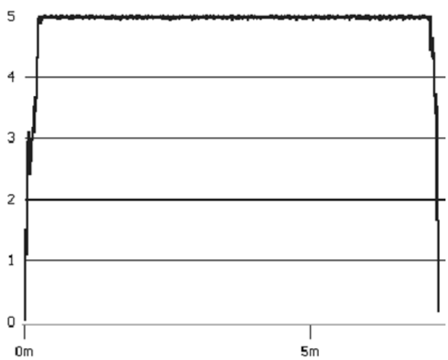

Fig. 8. IP queuing delay low priority traffic (STATIC APPROACH)

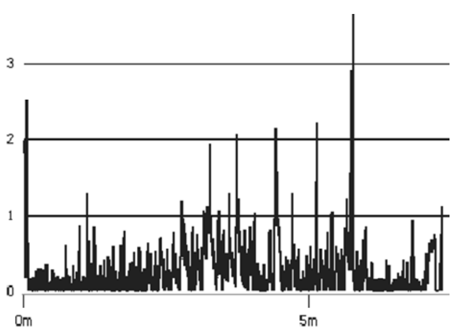

Fig. 9. MAC Queuing Delay Best Effort Traffic (STATIC APPROACH)

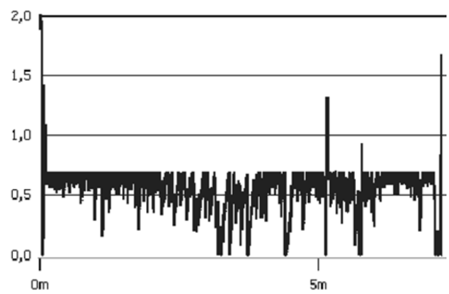

Fig. 10. MAC Queuing Delay Non Real Time Traffic (STATIC APPROACH)

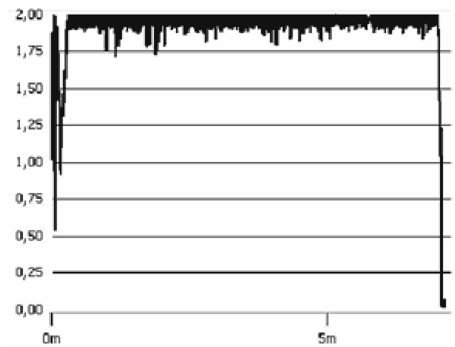

Fig. 11. IP Queuing delay Non Real Time (DYNAMIC APPROACH)

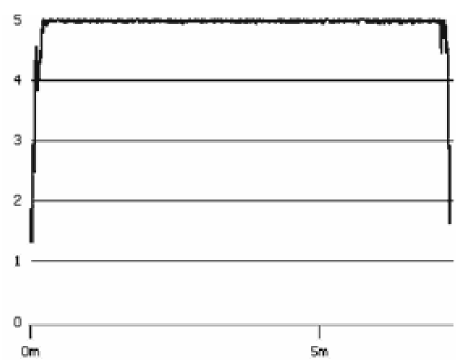

Fig. 12. Queuing delay Best Effort (DYNAMIC APPROACH)

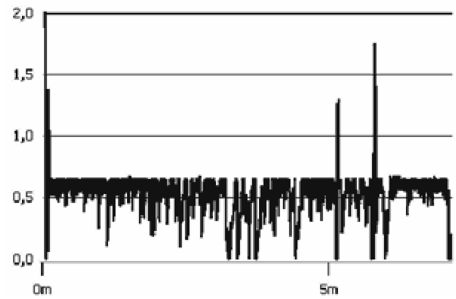

Fig. 13. MAC Queuing delay Non Real Time (DYNAMIC APPROACH)

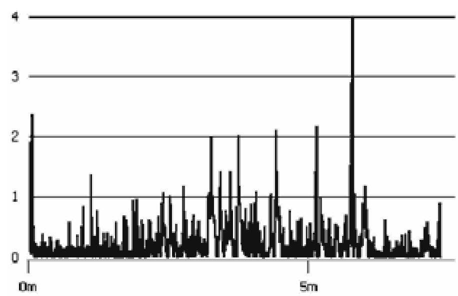

Fig. 14. MAC Queuing delay Best Effort (DYNAMIC APPROACH)

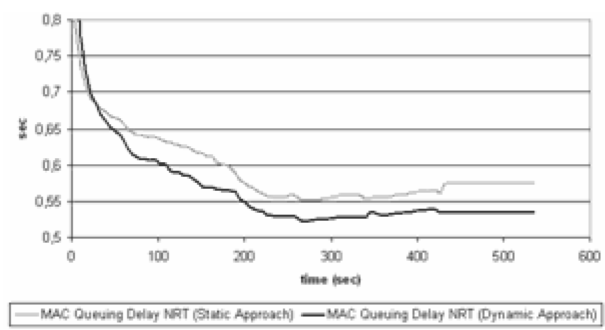

Fig. 15. Non Real Time MAC Average Queuing Delay comparisons

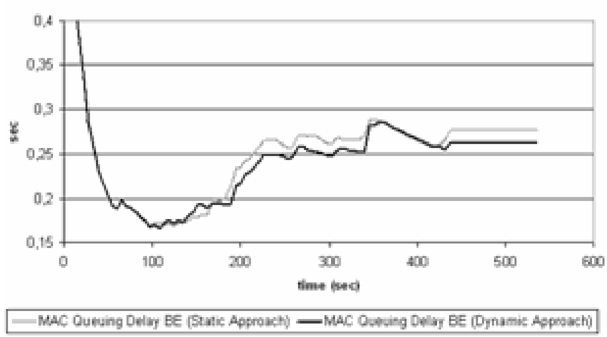

Fig. 16. Best Effort MAC Average Queuing delay comparisons

7 Conclusions

The proposed approach is built on the problem of cross-layer control between IP and MAC level. By computing a threshold that sets the maximum value that MAC queues can reach, it is possible to stop the traffic flow from IP to MAC level in congestion states. Both a worst-case static and a dynamic threshold were theoretically computed based on the control theoretical BoD scheme proposed in [22].

Summarizing the chosen approach meets the following targets:

- it avoids the duplication of the scheduling and dropping functionalities at the IP and MAC layers;
- It avoids MAC buffer overflows and consequent MAC cells dropping, which would result in partial transmissions of IP packets;
- when a congestion state occurs, packets are accumulated in the IP queues and not in the MAC queues, so that, in case of need, packets are dropped at IP layer; as the congestion ends, the IP scheduler is able to use all its discrimination capability by selecting the IP packets with the most stringent delay requirements.

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