An IP cross-layer scheduler for QoS provisioning in NGNs

Abstract: Next-Generation Networks (NGNs) will support Quality of Service (QoS) over a mixed wired and wireless IP-based infrastructure. A relative model of service differentiation in Differentiated Services architecture is a scalable solution for delivering multimedia traffic. However, the dynamic nature of radio channels makes it difficult to achieve the target quality provisioning working at the IP and lower layers separately as in the classical approach.

In this work, an IP cross-layer scheduler able to support a Proportional Differentiation Model (PDM) for delay guarantees also over wireless is described. The key idea is to leverage feedbacks from the lower layers about the actual delays experienced by packets in order to tune at run-time the priority of the IP queues with the objective of supporting a PDM at the network node on the whole across multiple layers.

A simulation analysis demonstrates the reliability and robustness of the proposal in achieving consistent results even with highly time-variant performance of the MAC and PHY layers, differently from the classical approach. Furthermore, considerations on the required additional functionality and likely deployment scenarios highlight the scalability and backward compatibility of the designed solution.

Keywords: cross-layer design**,** DiffServ, feedbacks, measurement process, Next-Generation Networks, PDM, QoS, scalability, wireless.

1. Introduction

Next-Generation Network (NGN) [1], is an IP network with Quality of Service (QoS) support and able to efficiently transport heterogeneous traffic. As summarized in [2], ITU recommendations G.1010, Y.1541 and Y.1221 collect the requirements of popular applications. Typically, these standards distinguish between interactive applications, like phone call, non-interactive applications, like video streaming, and best effort applications, like web browsing. The formers need that a specific set of quality parameters (e.g. end-to-end delay or loss) are guaranteed for all the packets or a given high percentage of them.
Different levels of service can be provided by IETF Differentiated Services (DiffServ) [3] in a scalable manner. Primarily, this architecture focuses on aggregates of flows in the core routers, and differentiates between service classes rather than providing absolute per-flow guarantees. More specifically, while the access routers process packets on the basis of high traffic granularity, such as per-flow or per-organization, core routers do not maintain fine grain state, and process traffic based on a limited number of Per Hop Behaviours (PHBs) encoded in the packet header, namely in the DiffServ Code-Point (DSCP) field [4]. Diffserv is gaining consensus as the QoS paradigm for NGNs, primarily because it moves the complexity of providing quality guarantees out of the core and into the edges of the network, where it may be feasible to maintain a restricted amount of per-flow state.
Broadly speaking, the proposals available in literature for supporting QoS can follow either an absolute or a relative approach for DiffServ [5]. The former aims to provide QoS on an absolute scale for each service class. While, the latter is able to offer a service differentiation between classes, i.e. a class can grant a lower delay or loss than another in a qualitative manner. Absolute DiffServ has some drawbacks and appears complex to

implement in the global Internet [5], whereas the Relative DiffServ is simpler and more suitable to be use with multimedia applications, which in some cases can even adapt to variations in network performance.

Many algorithms have been proposed [6] to realize Relative DiffServ, but the more promising ones, also for an efficient resource exploitation, are based on the Proportional Differentiation Model (PDM) [6], in which the performance distance between classes is proportional to given differentiation parameters that can be configured as needed.

However, the underlying hypothesis about the IP-based models for QoS provisioning, is that the lower layers are transparent, in other words, the bottleneck is at the network level. This is mostly true indeed, when wired transmission technologies (e.g. optical links, copper cables) are used, but it is not verified in general when we are dealing with air interfaces, especially in the access part of the wireless networks where the radio channel can be narrowband and highly time-variant in characteristics and hence performance.

The objective of this work[1] is to design a cross-layer scheduler at IP layer that allows for the possibly highly dynamic behaviour of the MAC and PHY layers in supporting a proportional model for QoS, considering the first three layers of the protocol stack on the whole. In detail, an IP node even on wireless interface should provide a delay differentiation between service classes according to the mutual ratio of (pre-)assigned quality factors, taking into account the cumulative latency in crossing the IP, MAC and PHY layers by packets before being transmitted.

The designed cross-layer scheduler is flexible enough to work in conjunction with a large variety of MAC scheduling and queuing mechanisms and policy, assuring reliability, robustness and scalability. Indeed, a proportional model for QoS is supported well in accordance with the mutual ratio of the quality factors assigned to the service classes (reliability), in different and possibly critical (i.e. extremely time-variant lower layer performance) working conditions (robustness), and with a low complexity (scalability) that makes the designed scheduler suitable also for the DiffServ networks, which include the Next-Generation of Mobile Networks (NGMNS).

The remainder of the paper is organized as follows. In Sect. 2, the state-of-the-art about achieving QoS in DiffServ architecture with a PDM, as well as the related open issues are reported. In Sect. 3, the proposed IP cross-layer scheduler is presented. Sect. 4 describes the investigated simulation scenarios, while Sect. 5 discusses the collected results, making also a comparison with the classical approach wherein the layers work in isolation. Finally, Sect. 6 outlines the main conclusions and future developments.

2. QoS in DiffServ and open issues

Proportional Differentiation Model (PDM) [5] for QoS yet allows for controllability, consistency, efficient resource exploitation and scalability. Refs. [5] and [6] explain how it is possible to use packet forwarding mechanisms to implement such a model at IP layer by a joint scheduling-dropping method to enforce proportional average delay and packet loss. Specifically, (Advanced) Waiting Time Priority ((A)WTP) schedulers [7] can approximate the proportional delay differentiation model also in short timescales, because in these schedulers the priority of a packet increases proportionally to its waiting time according to (the reciprocal of) the quality factor assigned to the issued queue.

Various approaches have been also proposed in literature for achieving absolute service bounds still relying on a proportional model. They can be divided into two groups: single-hop and end-to-end approaches. In the former, the absolute quality requirement can be

[1] The work has been carried out within the framework of the IST CONCERTO project, partially supported by the European Commission under the contract FP7 n°INFSO-ICT-288502.

addressed with a joint packet scheduling and dropping algorithms [8] and [9]. In the latter, various strategies proposing a run-time change of service class for the real-time traffic are available. Either the end-to-end delay [10] [11] or the loss [12] of the real-time traffic is monitored and if the related Service Level Agreement (SLA) is not met the traffic is moved to a higher priority class, otherwise it can be moved to a lower one. Another end–to-end approach considers the goodput of traffic flows [13] as target parameter in the management of the PDM scheduler, introducing additional functionality for measuring and conditioning the traffic in the border routers.

However, burst of traffic or class change introduces jitter [11] and could entail inconsistency in supporting a PDM [10]. Moreover, such an issue can definitely arise in case the lower layers are not transparent. This is likely to happen for example, when wireless interfaces are concerned. Indeed, the dynamic nature of the radio channel can lead to high delay and loss variability, which cannot be controlled at the IP layer, where the PDM is provisioned. To cope with this problem, various scheduling and queue management techniques have been introduced at the lower layers (i.e. MAC and PHY) in order to give priority to the critical traffic [13], even differently within a single flow [15].

But, the time-variant performance of the radio channel still entails unpredictable delays with the result that the service proportionality between the classes as configured at the IP layer can be seriously compromised (see also Sect. 5). There is yet a solution that proposes to shift the PDM support from IP to MAC layer, able to offer delay differentiation and loss proportionality between priority queues, while maximizing the throughput over a multi-state wireless channel [16]. However, it has limited applicability and does not consider the actual run-time IP layer performance in the PDM provisioning.

The key point is that the network and lower layers traditionally work in isolation and if there is a bottleneck at a given level, a consistent QoS model cannot be supported at the concerned interface on the whole. Such considerations highlight the need for a cross-layer design and optimization, at least in the critical points of the network.

In this respect, Ref. [16] is a first attempt towards a multi-level solution aiming to address a proportional delay differentiation. It relies on the WTP discipline for intra-node scheduling at the network layer and on an ad-hoc priority mapping between IP and MAC service classes for inter-node distributed coordination. But, this solution is suitable only for nodes in range of a WLAN and the setting of configuration parameters (the cut-off points for class mapping) is critical and computationally complex, with proposed heuristics that can have a bad impact on the reliability and stability of the resulting PDM implementation.

3. Efficient PDM support

The main objective of this work is to design a cross-layer scheduler at IP layer that is able to provide a delay differentiation between service classes according to assigned quality factors (QFs) considering the cumulative latency in crossing the IP, MAC and PHY layers by packets before being transmitted. It should be flexible enough to be applied with different (wired and) wireless technologies (i.e. 802.11, LTE or WiMAX), channel conditions and nodes settings.

Consistently, compensating actions at IP layer on the basis of current lower layers behaviour and performance entails the re-active nature of the scheduling algorithm to be devised in terms of dynamic tuning of its configuration and operating parameters. Therefore, cross-layer communication, adaptation and optimization are required.

More precisely, feedbacks coming from MAC and PHY levels, which we can refer to a wireless interface as the most critical case, should provide information about the run-time transmission performance. Such feedbacks can be used to build either an analytical or a statistical model of the lower layers behaviour.

In literature [18] and [20], some works describe the formalization and use of the "Effective Capacity" theory. However, the complexity of the related model could reveal unbearable

for a dynamic tuning of the operating parameters (due to the needed continuous re-building of the model), especially when high bit-rate links are issued as in NGMNs. Furthermore, an ad-hoc development is required for the specific scheduling discipline applied at MAC layer [20]. To avoid such risk and limitation, a statistical model could be employed instead. But, allowing for a fine granularity in the dynamic adjustment of the designed cross-layer scheduler parameters, it is more reliable to consider a short-term estimation of the delay for a given service class, as a punctual (i.e. single) value to be calculated by filtering the measurements of the delay experienced by packets at the MAC and PHY layers in that class. Noticeably, a filtering process (i.e. averaging) helps in assuring scalability and robustness of the proposed solution by reducing the number of triggered adaptation actions, in spite of quick and possibly impulsive, changes in the radio channel characteristics.
A suitable option for the cross-layer scheduler is the AWTP [21], where the IP packet service priority is simply determined by considering both the queuing delay and the QF assigned to each queue at the network layer. Indeed, it can efficiently support a delay differentiation between classes according to the mutual ratios of the assigned QFs, especially in high load conditions (i.e. the critical case) and with a limited number of queues (as in a DiffServ architecture) [21].
In our proposal, the priority of the IP packets for a given class increases when higher delays are likely to be experienced in that class at the lower layers, with the aim of supporting a PDM at the concerned interface on the whole.
The actual effect is that a lower queuing delay can be granted at the network layer when poor performance is expected at the MAC and PHY ones for the concerned class.
A mapping between the traffic aggregates at the IP and lower layers should be defined, because the delay feedbacks are to be correctly bound to the corresponding IP class.
For the purpose, the AF PHB [22] can be used. It allows for three subclasses within the same PHB, which can be used for a differentiated treatment at the lower layers (even if assigned with the same QF at the IP layer). This is for differently prioritizing packets of the same aggregate or even flow at the transmission interface on the basis of the importance or impact of the related content on the user Quality of Experience (QoE), for example in the case of video streams that are coded in different frame types (i.e. I, P and B) or layers (i.e. base and enhanced) [15]. This is also proposed by the recent IEEE 802.11aa standard [19], where for each MAC access category (i.e. priority class) 6 different transmission queues for intra-access category scheduling are introduced.
In practice, the number of feedback sequences coming from the lower layers equals the number of MAC (sub-)queues. Leveraging the AF PHB as in-band signalling between the issued layers for a consistent packet classification (hence, also queuing and scheduling), three sequences of delay estimations for each IP class of service should be provided at most. If C is the cardinality of the IP queues (i.e. supported instances of the AF PHB), the number of packets to be considered for each scheduling (i.e. number of service priority calculations) is 3C, where for each queue, the Head of Line (HoL) packet of every sub-queue is to be regarded. Therefore, the complexity of the designed cross-layer scheduler is still linear in the number of classes [21]. Furthermore, the additional computation associated with the filtering process of the delays experienced at the lower layers is negligible, requiring a constant (and small) number of basic algebraic operations per issued service class (see also Subsect 3.2) and being triggered at every packet transmission only.

3.1 – Service Priority calculation

In this subsection, the formula applied by the designed cross-layer scheduler for the service priority calculation of an IP packet is precisely specified. It is executed for each HoL packet

of an AF PHB (sub-)class related queue when a new packet can be sent to the lower layers for transmission. Of course, the packet with the highest priority among them is selected.
AWTP scheduler employs a pseudo-service technique [21], which virtually transmits each HoL packet to ascertain the *virtual waiting times* of all HoL packets after it has been transmitted. Let $w_j(t)$ be the waiting time of the class-j HoL packet at time t, $T_j(t)$ be its transmission time and $MACMA_j(t)$ the estimated value of the delay at the MAC and PHY layers for the class-j. When the pseudo-served packet belongs to class i, the proposed scheduler calculates the virtual normalized waiting time of class j, $\tilde{V}^i{}_j(t)$, and obtain the maximum proportion, $MP_i(t)$ as:

$$\tilde{V}^i{}_j(t) = \frac{w_j(t) + MACMA_j(t) + X_i}{QF_j} \qquad X_i = \begin{cases} 0 & if \quad i = j \\ T_i(t) & if \quad i \neq j \end{cases} \tag{1}$$

$$MP_i(t) = \max_{1 \leq j \leq N} \tilde{V}^i{}_j(t), \tag{2}$$

where X_i is the extra waiting time caused by transmitting the class-i HoL packet.
For every class i, its corresponding $MP_i(t)$ is calculated. Then, the maximum value of all $MP_i(t)$, and corresponding index are respectively given by:

$$MMP_i(t) = \max_{1 \leq i \leq N} MP_i(t) \tag{3}$$

$$C(t) = \arg\max_{1 \leq i \leq N} MP_i(t) \tag{4}$$

Finally, the AWTP scheduler chooses the HoL packet of class $C(t)$ for transmission.

3.2 Estimation process

As already pointed out, the filtering process applied to the values of the packet latency at the MAC and PHY layer is critical for achieving both system reliability and robustness against quick changes in the radio channel conditions. Indeed, the delay trend for each service class should be followed accurately enough, but without compromising the overall stability of the system in supporting a PDM.
Furthermore, providing a punctual estimation of the expected delay at the lower layers for each service class (rather than a sequence of values of packet delays) as input to the IP scheduler helps in avoiding scalability issues, since the processes can be implemented at the MAC layer directly, thus limiting the amount of data that needs to be communicated from the data-link to the network layer. It is worthwhile to point out that transmission cards available on the market can already provide measurements about the run-time performance on the interface [23], which can be exploited as well. In this case, no additional computational effort is necessarily introduced.
Alternatively, the filtering process can be implemented (typically, in software) and executed at the IP layer in order to improve the backward compatibility of the proposed solution.
Simple and suitable options for the filtering of the packet delays are the moving and exponential averages. In the case of moving average, at the lower layers, the queuing delay D_F experienced by each packet frame in a given queue is taken. K consecutive values of D_F related to the same service class queue are stored and when a new value is available, the oldest one is discarded (actually, obsolete values can be discarded as well). The filter output MA (delay estimation for the considered service class) is calculated as follows:

$$MA = \sum_{i=0}^{i=K} D_F \Big/ K \tag{5}$$

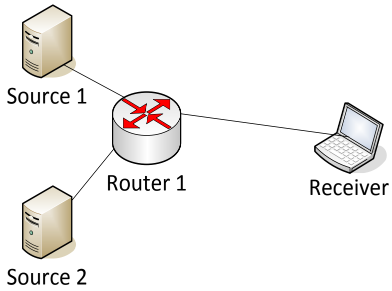

Figure 1 - Reference network scenario for the simulation analysis.

Hence, a single operation is required when a new sample is available (i.e. at every packet transmission on the physical media).
A proper setting for the relevant configuration parameters of the filtering process should be made. It can depend on the issued technology, selected access mode, bit-rate, number of supported service classes, and type of link (either in the access or core of the network, mobile or fixed, in an urban or in a rural area) as well as on limitations dictated by the specific network card implementation.
Finally, considering real traffic scenarios, it can happen that a certain service class has nothing to transmit for quite a time. In this case, a reasonable estimation about the latency expected at the lower layers in that class, to take into account in the priority calculation by the scheduling algorithm for a newly arrived IP packet destined to that class, can be an interpolation or simply the average, of the estimation figures related to the classes at the MAC layer closest to the concerned class in terms of service priority.

4. Simulation scenario

The designed IP cross-layer scheduler has a general validity and can be deployed in both wired and wireless interfaces. However, the simulation analysis is presented for the latter only, being the more critical case. Indeed, the dynamic nature of the radio channel can cause a high variability in the delay experienced by packets at the lower layers, which hardly happens with optical or copper links.
The simulation analysis has been carried out in a network scenario with two sources of traffic aggregates and one router, (see Figure 1), which deploy a PDM for QoS on output links of 100 Mbit/s (the other links are set to a higher capacity in order to be transparent). Eventually the router sends the traffic to the receiver.
Each source generates a traffic aggregate for every class of service composed of different types of flows as taken by real traces [24][25]:

- 1 TCP flow backbone aggregate, which represents the Best effort traffic, with an average rate of 21.7 Mbit/s,
- 1 MPEG4 generic video flow, which represents video streaming traffic, with an average rate of 128 Kbit/s,
- 1 MPEG4 video flow related to a person speaking, which represents video conference traffic, with an average rate of 260 Kbit/s.

With four service classes, this leads to more than 88 Mbit/s on average of overall traffic in each router input link.
At the router interface, operations are as follows:

- A filter drops about 45% of the incoming traffic, which means nearly 80 Mbit/s of the whole 176 Mbit/s. As a consequence about 98 Mbit/s is the amount of traffic that enters in the issued interface and that is sent to the receiver module;
- A classifier puts each incoming packet in the corresponding IP queue according to its DSCP value. Four AF PHB service classes (i.e. AF1, AF2, AF3 and AF4) are

supported at the network level, each with three sub-classes. For example, the PHB AF1 has the sub-classes AF11, AF12 and AF13 [22]. Therefore, the total number of IP (sub-)queues is 12;

- A server picks up packets from the IP queues applying the proposed cross-layer scheduling algorithm and sends them to the lower layers;
- A MAC-PHY module models the MAC and PHY layers differentiating the traffic between three service classes (queues), which correspond to the three sub-classes of each IP AF PHB, respectively. In detail, the traffic of the IP AF_{ij} sub-queues with i=1, 2, 3 and 4 enters the same MAC queue-j (with j=1, 2 and 3). Such module implements also the moving averaging process for each service class and updates the output of the concerned filter when a packet is sent on the air interface. Furthermore, it makes the delay estimations available to the server for the cross-layer scheduling algorithm calculations.

The Quality Factors (QFs) 1, 2, 3 and 4 are assigned to the four supported IP service classes AF1, AF2, AF3 and AF4, respectively. According to a PDM, the granted delay by the first class should be about half the delay by the second class and a third of the delay by the third one; while, the granted delay by the second class should be about half the delay by the fourth one, and so on. Buffers are big enough to avoid losses.

It is worthwhile to point out that the three IP sub-queues related to a given AF PHB are assigned with the same QF (e.g. AF11, AF12 and AF13 with 1), but a service differentiation in terms of delay for the corresponding traffic aggregates is applied at the lower layers.

Without loss of validity and generality for the performed analysis, the MAC and PHY layers are modelled as a black box, providing quality of service guarantees as in an LTE network [26]. The LTE classes of service with Quality Class Identifier (QCI) 7, 4 and 8 are loaded with the traffic from the (sub-)classes AFx1, AFx2 and AFx3 (with x=1, 2, 3 and 4), respectively (while, there is no traffic in the other LTE classes). As by standard [27], the packet delay budget for them is 100, 150 and 300 ms, respectively. Consistently with the standard, the TCP traffic has been assigned to the (sub-)classes AFx3, the MPEG video streaming traffic to the AFx2 and the MPEG video conference traffic to the AFx1 (with x=1, 2, 3 and 4).

The delay experienced by packets at the lower layers in each service class is statistically modelled, constrained by the related budget D_m.

In mobile wireless systems, the radio channel delay statistical distribution depends on a large variety of factors, not only the radio channel conditions, but also the employed frequency allocation and scheduling algorithms, to name a few. Therefore, in the simulation analysis the delay statistical distribution is a parameter itself, together with its mean and standard deviation. Specifically, the Trunk-Normal distribution (a Normal distribution where only the positive values are extracted) is configured for the presented results.

In a network scenario where two user terminals communicate through an IP backbone (see Figure 2), half of the maximum end-to-end delay (i.e. the delay budget) $D_m/2$ can be

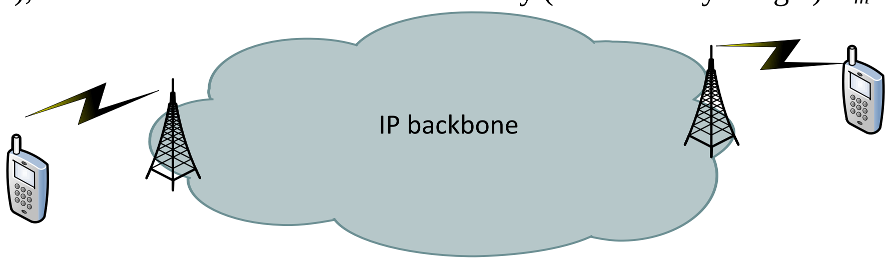

Figure 2 - Network scenario used for the LTE single hop maximum delay evaluation.

absorbed by the latter; while, the remaining can be equally allocated to the issued wireless connections (i.e. $D_m/4$ each).
Assigned the maximum value on the single radio interface, the mean is calculated as half of the maximum ($D_m/8$) and the standard deviation as half of the maximum divided by 6 ($D_m/48$), given that in the range ($-6\sigma/+6\sigma$) around the mean are included the 99.99% of the samples.
The mapping of the IP service classes onto the lower layers ones, together with the relevant configuration parameters for the delay are reported in Table 1.
It is to be underlined that the conclusions drawn out from the simulation analysis presented below do not actually depend on the specific settings. Indeed, similar results can be derived by investigating other network scenarios. Therefore, the considered parameters are not critical in the evaluation of the proposed solution. Also, the IP traffic could be differently marked, and hence classified within the AF (sub-)classes. For example, the packets of a same video flow can be distributed into the three (sub-)classes of AF1 (e.g. to apply a loss policy distinguishing between packets of different importance) and then served with a different priority at the lower layers [15] [19] (see also Sect. 3).

Table 1 – Class mapping and relevant delay figures.

MAC queue	**Mapped AF (sub-)classes (x=1,2,3,4)**	**LTE QCI**	**Packet delay budget [ms]**	**Maximum interface delay [ms]**	**Mean [ms]**	**Std. dev. [ms]**
1	AFx1	7	100	25	12.50	2.08
2	AFx2	4	150	37.50	18.75	3.12
3	AFx3	8	300	75	37.50	6.25

5. Simulation results

The aim of this section is to show the reliability and robustness of the proposed IP cross-layer scheduler in supporting a PDM for QoS, by discussing the achieved performance with the investigated design and configuration options.
It is worthwhile to recall that the more the delay differentiation between the service classes is in line with the mutual ratios of the (pre-)assigned QFs, the more the PDM is well supported. The delay is to be considered at the issued interface on the whole (i.e. the cumulative value of the latencies experienced by packets at the network and lower layers).
The evaluation has been carried out by OMNET 4.0 [28], as a reliable and popular open-source simulation tool.
The sources generate the traffic aggregates as specified in the previous section from the simulation starting, while the results are collected after the end of the initial transitory period of 5 s.
The parameter K of the moving average (as defined in Subsect. 3.2) is set to 10 (for every MAC service class), being a good trade-off between having a reliable estimation of the lower layers delay in the short-term (which in turn leads to a higher adaptation capacity of the cross-layer scheduler in order to support the PDM) and stability of the system in spite of quick and possibly impulsive, changes in the radio channel performance (see also the analysis about the system robustness in the second part of this section).
We first evaluate the reliability of the proposed solution, which can be better appreciated by making a comparison with the classical approach wherein the IP and lower layers work in isolation.

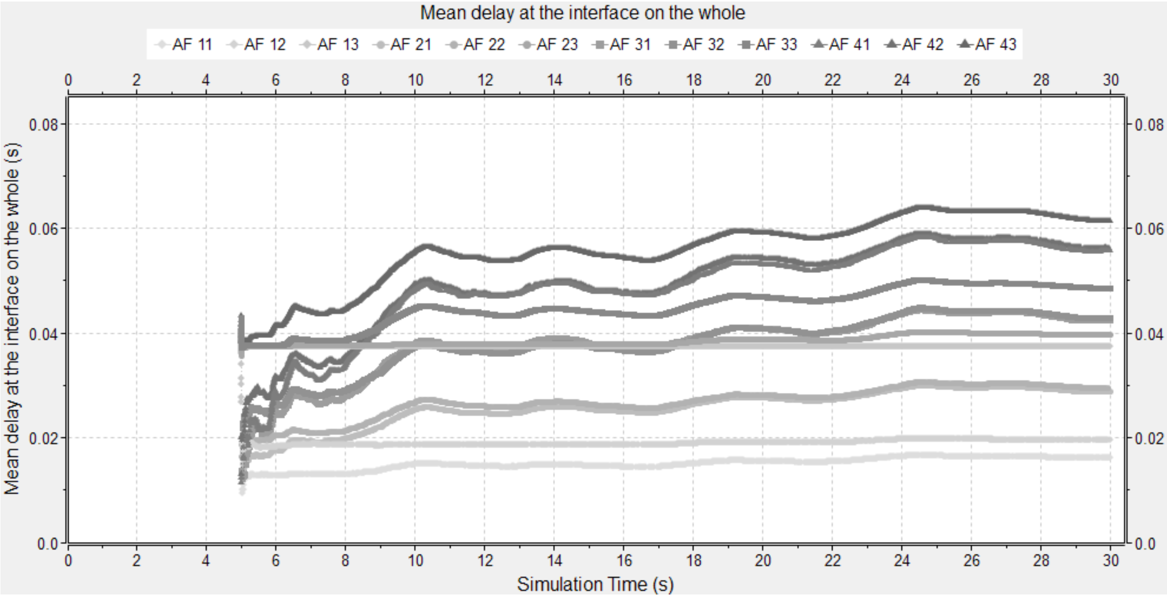

Figure 3 - Mean delay at the interface on the whole with the cross-layer solution.

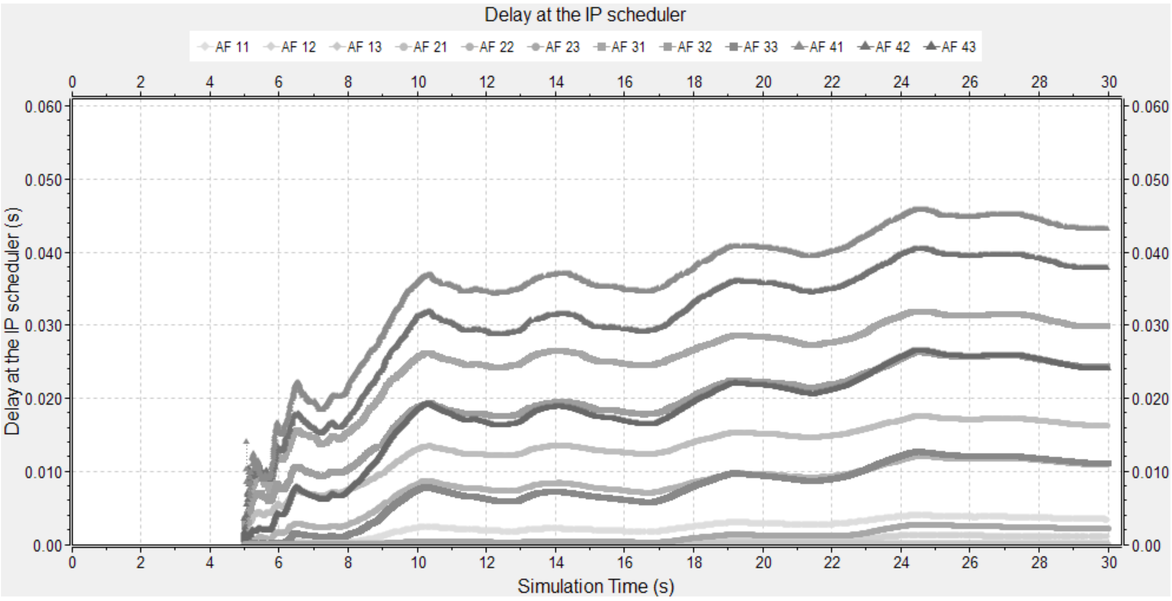

Figure 4 - Mean IP delay with the cross-layer solution.

Figure 3 and Figure 4 depict the mean delay at the interface on the whole and the mean IP delay (i.e. the delay measured just at the IP cross-layer enhanced AWTP scheduler egress), respectively. While, Figure 5 and Figure 6 depict for the classical approach in the same network and configuration scenario again the mean delay at the interface on the whole and the mean IP delay (i.e. the delay measured just at the classical AWTP scheduler egress), respectively. Table 2 reports the mutual ratio of the mean delays at the interface on the whole between some of the (sub-)classes of service with either the novel or the classical approach.

Looking at the figures, we can see how the proposed solution is able to differentiate the classes of service according to the mutual ratio between the corresponding QFs.

Such good results are more evident making a comparison with the classical approach. Indeed, in that case the delays at the interface on the whole for the 12 (sub-)classes of service (AF_{ij}, with i=1, 2, 3, 4 and j=1, 2, 3) are divided into three groups (i.e. corresponding to the 3 issued LTE service classes), because the MAC delay is not negligible with respect to the IP one (i.e. the hypothesis that the lower layers are transparent does not hold), and not considered in the service priority calculation by the classical AWTP scheduler at the IP layer. Though, the granted delay at the network layer are more consistent with a PDM in the classical approach (the mean delays of the 12 (sub-)classes are divided into four groups, according to the number of configured IP AF PHBs), as also reported in Table 3.

Furthermore, the figures in Table 2 refer to (sub-)classes mapped onto the same MAC queue, which even represents a better term of comparison for the classical approach (that completely disregards the lower layers service differentiation).

It can be deduced as the proposed solution can provide better and better performance as the IP queuing delay is in general higher and higher than the lower layers delay. Because, in this case the cross-layer scheduler can compensate more the MAC and PHY latencies, increasingly differentiating the service classes at the network level in order to support a PDM at the interface on the whole.

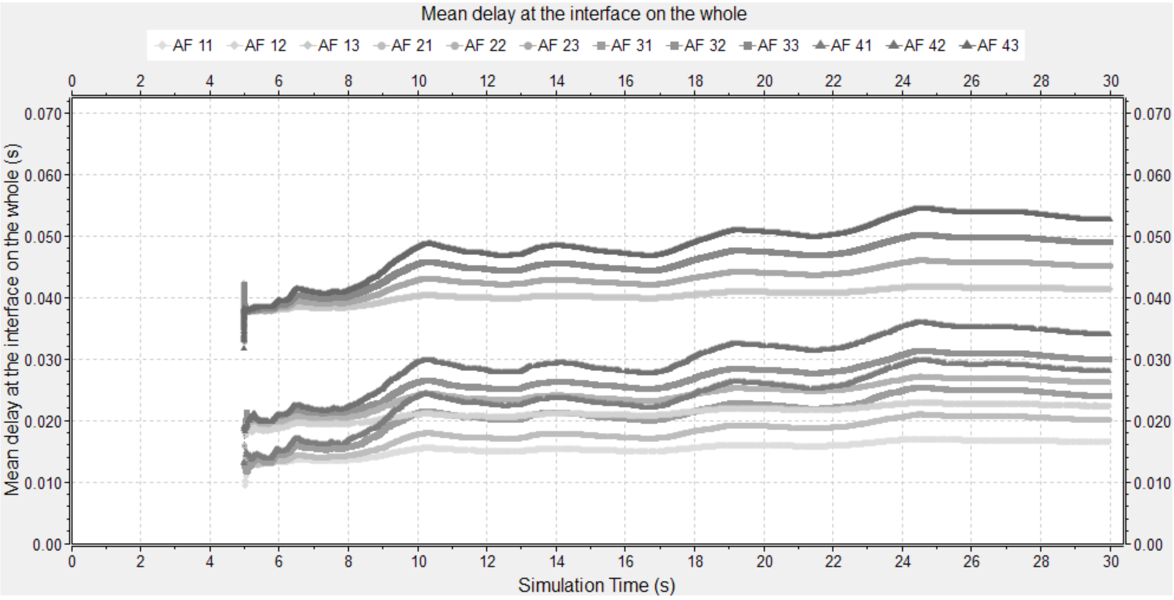

Figure 5 - Mean delay at the interface on the whole with the classical solution.

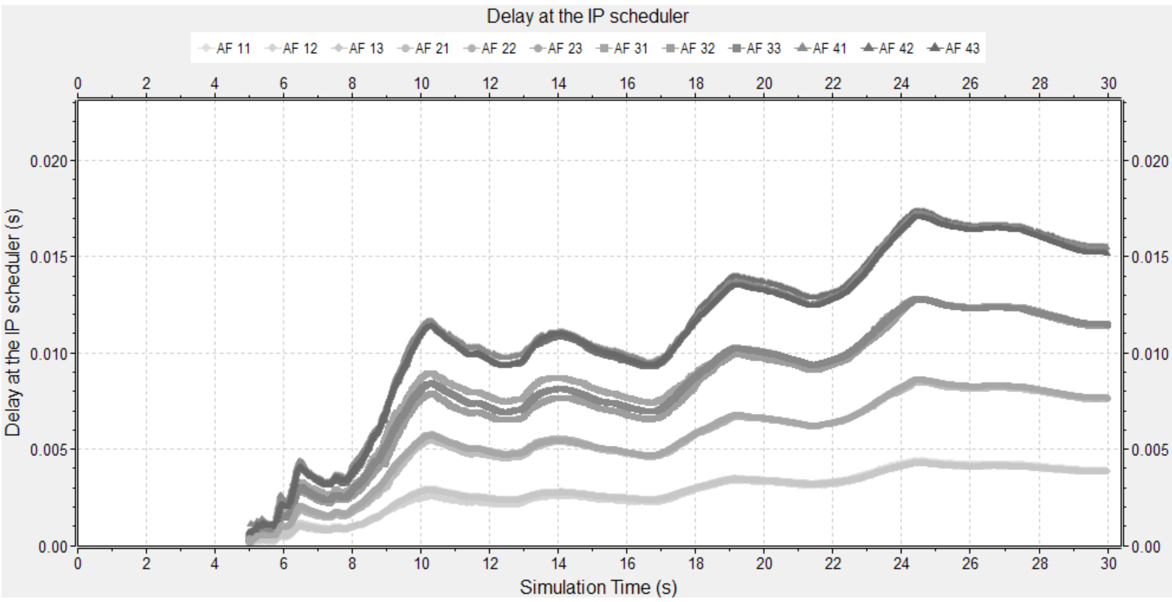

Figure 6 - Mean IP delay with the classical solution.

Table 2 - Mutual ratio of the delays at the interface on the whole for some of the (sub-)classes of service (AF11, AF21, AF31 and AF41) with either the innovative (CL) or the classical (No CL) approach.

QFs ratio	CL [ms]	No CL [ms]
1/1	1	1
2/1	1.82	1.21
3/1	2.55	1.41
4/1	3.36	1.64

Table 3 - Mutual ratio of the IP delays for some of the (sub-)classes of service (AF11, AF21, AF31 and AF41) with either the innovative (CL) or the classical (No CL) approach.

QFs ratio	CL [ms]	No CL [ms]
1/1	1	1
2/1	5.18	1.97
3/1	9.38	2.92
4/1	13.77	4.02

The second set of results aims to verify the robustness of the proposed solution with respect to environment changes, i.e. it should remain reliable in any working and possibly quite variable, conditions. Mainly, two possible cases of environment change can be envisaged: traffic or radio channel behaviour variations. Considering that the cross-layer scheduler can inherently well support a PDM in high load conditions, even with extremely bursty traffic [21], only the latter case is worthy of investigations.

For the purpose, the lower layers delays are statistically modelled again with a Trunk-Normal distribution (discarding the values out of the admissible delay range) with an increased variance. Still keeping the maximum acceptable delay at the wireless interface, as by LTE standard (see Sect. 4), the configured new values of the mean and standard deviation for the three lower layers service classes are reported in Table 4.

Table 4 - Class mapping and relevant delay figures.

MAC queue	Mapped AF (sub-)classes (x=1,2,3,4)	LTE QCI	Packet delay budget [ms]	Maximum interface delay [ms]	Mean [ms]	Std. dev. [ms]
1	AFx1	7	100	25	5	3.33
2	AFx2	4	150	37	7.40	4.93
3	AFx3	8	300	75	15	10

Table 5 - Mutual ratio of the delays at the interface on the whole for some of the (sub-)classes of service (AF11, AF21, AF31 and AF41) with either the innovative (CL) or the classical (No CL) approach.

QFs ratio	CL [ms]	No CL [ms]
1/1	1	1
2/1	1.64	1.23
3/1	2.38	1.51
4/1	3.10	1.79

The obtained results are quite similar to those related to the former modeling of the lower layers performance. Table 5 collects the mutual ratio of the mean delay at the interface on the whole for the (sub-)classes of service AF11, AF21, AF31 and AF41 with either the cross-layer or the classical approach. The reported figures demonstrate how the proposed IP cross-layer scheduler is able to honor a PDM also in the case of higher variability of the lower layers delay. While the classical solution shows again its limitations (i.e. when the radio channel is not transparent).

Regarding the variance of the delay introduced at the router interface on the whole, the proposed IP cross-layer scheduler actually tries to balance increasing lower layers delays (and decreasing ones as well) for a given service class (because it takes into account an estimation of the radio channel performance for that class in the IP service priority calculation) by granting a decreased (or increased in case of improved delays at the lower layers) IP delay (with respect to the value granted in the previous conditions) with the aim of respecting as reliably as possible the proportional delay differentiation between the classes specified by the mutual ratio of the (pre-)assigned QFs. In principle, this leads to a reduced variability on the delays considering (separately) all the service (sub-)class at the router interface. However, the resulting effect of the cross-layer optimization on the delay variation for a given service class depends also on the absolute values of the QF other than their mutual ratios, as well as on the order of the lower layers delays, which makes it difficult to evaluate its specific impact beforehand.

As a general but outstanding consideration, it is important to underline that the packets of a single traffic flow, whose jitter has an impact on the QoE perceived by the addressed end-user (e.g. in the case of real-time multimedia applications), could be classified into multiple (sub-)classes of a single AF PHB (e.g. AF11, AF12 and AF13 of AF1). For an improved QoE, IP (sub-)classes of the same AF PHB can be mapped onto different MAC queues [15] [19] (as also operated in the presented simulation analysis, being more critical in supporting a PDM on the whole at the interface). Given that different lower layers classes grant different delays, this is the case where the proposed solution demonstrates most its superiority with respect to a classical approach. Indeed, when the network and lower layers work in isolation the packets in a AF PHB class (e.g. AF1) are scheduled with the same priority at the IP level independently from the specifically assigned sub-class of the said AF PHB, while possibly experiencing largely different performance at the lower layers (compromising in this way the reliable support of a PDM at the interface on the whole).

6. Conclusions

This paper presents a solution for the efficient support of a Proportional Differentiation Model (PDM) for Quality of Service (QoS) in Next-Generation Networks (NGNs), leveraging cross-layer communication and optimization strategies over Differentiated Service (DiffServ) architecture. A delay differentiation between the IP AF PHB service classes instantiated at the network node according to the mutual ratio of (pre-)assigned Quality Factors (QFs) is provided considering the issued interface on the whole. Therefore, the proportionality for the granted performance is on the cumulative delay experienced by the packets at the network and lower layers.

The proposal is based on an enhanced version of a well-known and low-complexity IP scheduler (i.e. AWTP). The key idea is to determine the service priority for a Head of Line (HoL) packet in a AF sub-class (e.g. AF11, AF12 and AF13 for AF1 PHB) taking into account also the expected delay at the MAC and PHY levels (other than the IP queuing delay) for the traffic of that (sub-)class. For the purpose, cross-layer signalling by the in-band DiffServ Code-Point (DSCP) from the network to the lower layers for a consistent classification and queuing, and by delay feedbacks in the opposite direction is used. More specifically, an estimation of the latency at the lower layers for each supported service (sub-)class is calculated applying a filtering process to the values of the delay experienced by the packets in the class, and made available at the network layer. The cross-optimization ensures reliability and robustness also in case of wireless interfaces, where the dynamic nature of the radio channel can entail extremely time-variant performance. Conversely, the classical approach for IP QoS, where the network and lower layers work in isolation, shows serious limitations when the MAC and PHY levels are not transparent. In this respect, the designed solution could be deployed in critical point of the network (e.g. on the wireless interfaces) only as for an improved backward compatibility. A fully software-based implementation and the applicability to the large variety of lower layer technologies,

mechanisms and policies that aim at providing a service differentiation between classes on a delay basis, also demonstrate such a property of our proposal.
Furthermore, the low complexity of the additional functionality and operations with respect to the classical approach do not jeopardize the scalability of the addressed PDM over DiffServ architecture.
The proposed solution has been assessed by simulation analysis applying a statistical modelling of the lower layers delays with maximum values according to the LTE standard for the real-time, streaming and best-effort traffic, respectively.
Both reliability and robustness have been evaluated. The collected results show that the delays granted to the instantiated (sub-)classes of service are well in line with the mutual ratio of the (pre-)assigned QFs at the network level, considering the issued router interface on the whole, even with different (and high) variability of the lower layers performance.
A PDM for QoS is reliably supported also in the critical case when the sub-classes associated with the same AF PHB are mapped onto different MAC classes, and hence queues. The classical approach demonstrates definitely unsuitable when the MAC and PHY layers delays are not negligible with respect to the IP one, and typically when a different priority is given at the lower layers to packets of a single traffic flow, though in the same IP service class (e.g. AF1), because related to different video frame types or layers of a coded video, which then experience different delays. While, the newly designed cross-layer scheduler can provide the required delay differentiation by taking into account the lower layers performance independently from the service policy employed at the MAC layer. Finally, the balancing actions applied at the IP layer for a consistent PDM support at the interface on the whole can reduce the jitter within a single traffic flow, with beneficial effects on the QoE of the addressed user.
Future work regards the performance analysis of the proposed solution with a detailed modelling of a specific transmission technology (e.g. LTE or Wi-Fi) in given radio channel conditions (e.g. slow or fast fading, interference level, SNR value) changing over time, with also other network scenario configurations (i.e. traffic aggregates, number of instantiated AF PHB classes, assigned QFs, link capacity and average load). Furthermore, different filtering processes for the lower layers delays estimations, together with the related operating parameters, can be also investigated for an improved reliability and robustness.

References

[1] ITU Y.2001, “General overview of NGN”, December 2004.
[2] D. Mustill and P.J. Willis, “Delivering QoS in the next generation network - a standards perspective”, BT Technology Journal, April 2005, Volume 23 Issue 2, pp. 48-60.
[3] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, W. Weiss, ”An architecture for Differentiated Services”, IETF Request for Comments (RFC 2475), url: http://www.ietf.org/rfc/rfc2475.txt, December1998.
[4] K. Nicholas, S. Blake, F. Baker, D. Black, “Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 Headers”, IETF Request for Comments (RFC 2474), http://www.ietf.org/rfc/rfc2474.txt, June 1999.
[5] C. Dovrolis and P. Ramanathan “A Case for Relative Differentiated Services and the Proportional Differentiation Model”, IEEE Network September/October 1999, Volume 13, Issue 5, pp. 26-34.
[6] C. Dovrolis, D. Stiliadis, P. Ramanathan, “Proportional differentiated services: delay differentiation and packet scheduling”, in IEEE/ACM Transactions on Networking February 2002, Volume 10, Issue 1, pp. 12-26.
[7] Yuan-Cheng Lai, Wei-Hsi Li, “A novel scheduler for proportional delay differentiation by considering packet transmission time”, IEEE Communications Letters April 2003, Volume 7, Issue 4, pp. 189-18.
[8] Y. Chen, C. Qiao, M. Hamdi and D. Tsang “Proportional Differentiation: a scalable QoS approach”, IEEE Communications Magazine June 2003, Volume 41, Issue 6, pp. 52-58.
[9] D.L. Pham, S. Sugawara, T. Miki, “A new scheduler for real-time applications in differentiated services networks”, in Proc. IEEE/INFOCOM Conference March 2005, Volume 4, pp. 2841 - 2846.

[10] T. Nandagopal, V. Venkitaraman, R. Sivakumar, V. Bharghavan, “Delay Differentiation and Adaptation in Core Stateless Networks”, in Proc. INFOCOM, Conference March 2000, Volume 2, pp. 421–30.
[11] G. Panza, S. Grilli, “A scalable solution to provide Quality of Service in Next-Generation Networks”, in Proc. Future Network & Mobile Summit (FutureNetw) June 2011, pp.1-15.
[12] W. Wu, Y. Ren, X. Shan, “Forwarding a Balance between Absolute and Relative: A New Differentiated Services Model”, Proc. IEEE Workshop. High Perf. Switching and Routing May 2001, pp. 250–254.
[13] C. Simon, A. Vidacs, I. Moldovan, A. Torok, K. Ishibashi, A. Koike, H. Ichikawa, “End-to-end relative Differentiated Services for IP networks”, in Proc. ISCC Seventh International Symposium on Computers and Communications 2002, pp. 783- 788.
[14] T. Sutinen, J. Vehkaperä, E. Piri and M. Uitto, “Towards ubiquitous video services through scalable video coding and cross-layer optimization”, EURASIP Journal on Wireless Communications and Networking 2012, http://jwcn.eurasipjournals.com/content/2012/1/25.
[15] E. Piri, M. Uitto, J. Vehkaperä, T.Sutinen, “Dynamic Cross-Layer Adaptation of Scalable Video in Wireless Networking”, in Proc. IEEE Global Telecommunications Conference (GLOBECOM 2010), December 2010, pp.1-5.
[16] Yu-Chin Szu, “Using Debt Mechanism to Achieve Proportional Delay and Loss Differentiation in a Wireless Network with a Multi-state Channel”, in Proc. ISWPC 2009, 4th International Symposium on Wireless Pervasive Computing February 2009, pp.1-6.
[17] X. Yuan, C. Kai, K. Nahrstedt, “Distributed end-to-end proportional delay differentiation in wireless LAN”, in Proc. IEEE International Conference on Communications June 2004, Volume7, pp. 4367- 4371.
[18] D. Wu and R. Negi, “Effective capacity: A wireless link model for support of quality of service”, IEEE Trans. Wireless Commun., Volume 2, pp. 630–643, July 2003.
[19] IEEE 802.11aa-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 Amendment 2: MAC Enhancements for Robust Audio Video Streaming”, May 2012.
[20] C.-S. Chang and J. Thomas, “Effective bandwidth in high speed digital networks”, IEEE J. Select. Areas Commun., Volume 13, pp. 1091–1100, Aug. 1995.
[21] Yuan-Cheng Lai, Wei-Hsi Li, “A novel scheduler for proportional delay differentiation by considering packet transmission time”, IEEE Communications Letters, Volume 7, Issue 4, pp. 189-181, April 2003.
[22] J Heinanen, F Baker, W Weiss, J Wroclawski, “Assured forwarding PHB group”, IETF Request for Comments (RFC 2597), url: www.ietf.org/rfc/rfc2597.txt, June 1999.
[23] url: www.riverbed.com/us/products/cascade/wireshark_enhancements/airpcap.ph
[24] url: www-tkn.ee.tu-berlin.de/research/trace
[25] url: tracer.csl.sony.co.jp/mawi/
[26] 3GPP TS 36.300 v. 8.11.0, “Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access (E-UTRAN); Overall Description; Stage 2”,. January 2010.
[27] 3GPP TS 23.203 v. 8.8.0, “Policy and Charging Control Architecture”, December 2009.
[28] url: www.omnetpp.org/