Relative QoS provisioning over Next-Generation Networks

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***Abstract*— Next-Generation Networks (NGNs), comprising for example, 4G and B4G mobile systems, will support Quality of Service (QoS) over a heterogeneous 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 separately at the IP and lower layers, as in the classical approach. In this work, an IP cross-layer scheduler able to support a Proportional Differentiation Model (PDM) for delay guarantees is introduced. The key idea is to leverage feedback from the lower layers indicating the actual transmission delays experienced by packets in order to dynamically tune the priority of the IP service classes with the objective of supporting the PDM at the network node on the whole across multiple layers. A simulation analysis demonstrates the prominent improvements in reliability and robustness of the proposal with respect to the classical approach. Considerations on the required functionality and possible deployment scenarios highlight the scalability and backward compatibility of the designed solution. Therefore, it addresses the requirements and challenges for NGNs.**

Keywords*— *4G, B4G, cross-layer design, DiffServ, feedbacks, IP, measurement process, NGN, PDM, QoS, wireless.

I. INTRODUCTION

Next-Generation Networks (NGNs) [1], e.g., 4G and B4G mobile systems, are IP based networks with Quality of Service (QoS) support and able to efficiently deliver a variety of different kind of traffic. As described in [2], ITU recommendations G.1010, Y.1541 and Y.1221 collect the requirements of popular applications. Typically, these standards distinguish between best effort applications, such as web browsing, and real-time applications that can be further divided into interactive applications (e.g. phone calls) and non-interactive applications (e.g. video streaming). The real-time applications typically are delay and loss sensitive, which challenges networks to support guaranteed service levels for these applications.

De-facto standard for scalable QoS provisioning over IP networks is the IETF Differentiated Services (DiffServ) [3]. 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 Behaviors (PHBs) encoded in the packet header, namely in the DiffServ Code-Point (DSCP) field [4]. Diffserv has gained consensus as reference architecture for QoS support in NGNs, because it moves the operating complexity out of the core and into the edges of the network, where it may be more feasible to maintain a restricted amount of per-flow states.

In the end, the solutions available in the open literature for providing QoS can rely on either an absolute or a relative approach for DiffServ [5]. The former aims to support 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 is hard to achieve especially over a wireless network and it appears to be complex to implement on a large scale [5]. On the contrary, Relative DiffServ is simpler and more flexible to be used in dynamic network environments. It is also more suitable for multimedia applications, which mostly require QoS support, but are also often able to adapt according to network actual 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.

The objective of this work is to design a cross-layer scheduler at the IP layer that supports a proportional model for QoS also over radio channels, considering the first three layers of the protocol stack on the whole. In detail, it can provide delay differentiation between service classes according to the mutual ratio of (pre-)assigned quality factors, taking into account the expected cumulative latency of packets through the IP, MAC and PHY layers before actual transmission. The designed cross-layer scheduler is flexible enough to operate on both wired and wireless links. It can work in conjunction with a large variety of

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MAC scheduling and queuing mechanisms and policies, yet assuring reliability, robustness and scalability of the solution.

Indeed, a proportional model for QoS is supported at the interface on the whole well in accordance with the mutual ratio of the quality factors assigned to the IP service classes (reliability), in different and possibly highly fluctuating link conditions (robustness), and with low complexity (scalability). All this makes the designed scheduler suitable also for the DiffServ networks, which include the Next-Generation of Mobile Networks (NGMNS).

The rest of the paper is organized as follows. In Sect. II, the state-of-the-art about supporting a PDM with the open issues is reported. In Sect. III, the proposed IP cross-layer scheduler is presented. Sect. IV describes the investigated simulation scenarios, while Sect. V discusses the collected results with different design options and configuration settings, making also a comparison with the classical approach wherein the layers work in isolation. Finally, Sect. VI outlines the main conclusions and future developments.

II. PDM SUPPORT IN NGNS

PDM [5] for QoS yet allows for controllability, consistency, efficient resource exploitation and scalability. Packet forwarding mechanisms [5][6] can be used to implement such a model at IP layer by a joint scheduling-dropping method to enforce proportional average delay and packet loss. For example, (Advanced) Waiting Time Priority ((A)WTP) schedulers [7] can follow a proportional delay differentiation model also in short timescales.

However, inconsistencies arise when 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 alone, where the PDM is provisioned. To avoid this problem, various scheduling and queue management techniques have been introduced at the lower layers, typically at the MAC layer, in order to give priority to the critical traffic [8], even differently within a single flow [9].

Nevertheless, the time-variant performance of the radio channel can still entail unpredictable delays with the result that the service proportionality between the classes as configured at the IP layer can be seriously compromised looking at the issued interface on the whole.

There is yet a solution that proposes to shift the PDM support from IP to MAC layer, offering delay differentiation and loss proportionality between priority queues, while maximizing the throughput over a multi-state wireless channel [10]. However, it has a limited applicability and does not consider conversely the actual run-time IP layer performance in the PDM provisioning.

The key point is that the network and lower layers traditionally work independently and if there is a bottleneck at a given level, a consistent QoS model cannot be supported at the employed 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, such as on wireless access links.
In this respect, [11] 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 distributed inter-node coordination. However, this solution manages the nodes in range of a WLAN only (while, NGNs can span a good variety of different technologies). Furthermore, the setting of configuration parameters (the cut-off points for class mapping) is critical, computationally complex and the proposed heuristics can have a negative impact on the reliability, robustness and scalability of the resulting PDM implementation (which are requirements for the NGNs).

III. PROPOSED SOLUTION

Basically, the main objective of this work is to design a cross-layer scheduler at the IP layer that is able to provide delay differentiation between service classes according to (pre-) 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 and configuration settings, as well as to allow for the possibly very high dynamism of radio channels.

Taking into account the current behavior and performance of the lower layers entails the (re-)active nature of the scheduling algorithm introduced. Therefore, cross-layer communication, adaptation and optimization are required by the scheduling solution.

Feedback coming from the MAC and PHY levels can provide information about the run-time transmission performance indicating the current link condition. Such information can be used to build either an analytical or a statistical model of the lower layers' behavior.

In literature, some works [12][14] describe the formalization and use of the "Effective Capacity" theory about the MAC and PHY layers' actual performance. However, the complexity of the related model can be unbearable with respect to a dynamic tuning of the scheduler's operating parameters (due to the need for continuous re-building of the model), especially when wireless links are issued like in NGMNs. Furthermore, an ad-hoc development would be required for the specific scheduling discipline applied at the MAC layer [14]. To avoid such risks and limitations, a statistical model can be employed instead. However, allowing for a fine granularity in the dynamic adjustment of the designed cross-layer scheduler parameters, it is more consistent 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 transmission and queuing delay experienced by packets at the MAC and PHY layers in that class. Noticeably, a low-pass filtering process helps 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.

The design of our cross-layer scheduler follows the same strategy than AWTP [15]. Such a scheduling discipline can well support delay differentiation between classes at the IP layer according to the mutual ratios of the assigned QFs, especially, in high load conditions (i.e. lack of transmission resources) and with a limited number of queues (as in a DiffServ architecture) [15]. However, AWTP determines the IP packet service priority by considering the queuing delay at the network layer only.

The key difference and a significant benefit of our proposal is that 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 the PDM at the used interface on the whole.

Actually, 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 binding between the traffic aggregates at the IP and lower layers should be defined, because the delay feedback needs to be correctly associated with the corresponding IP class.

For the purpose, the AF PHB [16] can be used. It also provides three subclasses within the same PHB, which can be used for a differentiated treatment at the MAC and PHY layers (even if assigned with the same QF at the IP layer). This allows prioritizing packets of the same aggregate or even the flow at the lower layers according to the importance or impact of the related content on the user Quality of Experience (QoE). For instance, it could be applied to video streams that are encoded in different frame types (i.e. I, P and B) or layers (i.e. base and quality enhancement layers) [9]. This is also enabled by the recent IEEE 802.11aa standard [13], where for each MAC access category (i.e. priority class) six different transmission queues are supported per access category.

In practice, the number of feedback sequences originated from the lower layers equals the number of MAC (sub-)queues. Considering the AF PHB as in-band signaling between the issued layers for a consistent packet classification, three sequences of delay estimations for each IP class of service can be provided. If C is the cardinality of the IP queues (i.e. supported instances of the AF PHB at the issued interface), the number of packets to be considered for each scheduling (for which, the service priority needs to be calculated) 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 linear in the number of classes as in AWTP [15]. 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 Section III.B) and being triggered at every packet transmission only.

A. Service Priority calculation

The service priority is calculated for each HoL packet of an AF PHB class related (sub-)queue when the next packet can be sent to the lower layers. The packet with the highest priority among them is taken.

As in AWTP, a pseudo-service technique [21], is employed. It virtually transmits the HoL packet of each class-i Pi, to ascertain the *virtual waiting times* of all the HoL packets after P_i has been transmitted. Let $w_j(t)$ be the waiting time of the class-j HoL packet P_j 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 P belongs to class i, the proposed scheduler calculates the virtual normalized waiting time of class $j, \widetilde{V}^i{}_j(t)$, and obtain the maximum proportion, $MP_i(t)$ as:

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

$$MP_i(t) = \max_{1 \le j \le N} \widetilde{V}^i{}_j(t) \tag{2}$$

where X_i is the extra waiting time caused by transmitting the class-i HoL packet and QFj is the quality factor of class-j.

For every class i, its corresponding MPi(t) is calculated. Then, the maximum value of all MPi(t), and corresponding index are respectively given by:

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

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

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

B. Delay estimation

As already pointed out, the filtering process applied to the values of the packet latency at the MAC and PHY layer is critical for addressing both system reliability and robustness against quick changes in the radio channel conditions. In detail, 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 avoiding scalability issues. Indeed, the filtering processes can be also implemented at the MAC layer directly, 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 [17], which can be exploited as well. In this case, no computational effort for the estimation process is introduced.

Alternatively, such a process can be implemented (typically, in software) and executed at the IP layer in order to improve the backward compatibility of the proposed solution.

Suitable options for the filtering of the packet delays can be the moving and exponential averages.

In the case of Moving Average, the queuing delay D_F experienced by each packet frame at the lower layers in a given (sub-)queue is taken. K consecutive values of D_F related to the same (sub-)queue of a given service (sub-)class are stored and when a new value is available, the oldest one is discarded (obsolete values can be discarded as well). The filter output MA (delay estimation for the considered (sub-)class of service) is calculated as follows:

$$MA = \sum_{i=0}^{i=K} D_F \Big/ K \qquad (5)$$

In the case of Exponential Average, i.e. a simple Low-Pass filter with a single pole P (<1), the queuing delay D_F experienced by each packet frame at the lower layers in a given (sub-)queue and the last filter output LP_{old} related to the same service (sub-)class are used for calculating the new estimation *LP as*:

$$LP = LP_{old} \cdot P + D_F \cdot (1 - P) \qquad (6)$$

Actually, D_F alone is taken as a valid estimation when the last filter output is obsolete.

With both the described estimation processes, a single operation is required when a new delay sample is available (i.e. at every packet transmission on the physical media).

In practice, it can happen that a certain service (sub-)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 (sub-)class, to be taken into account in the priority calculation by the scheduling algorithm for a newly arrived IP packet belonging to that (sub-)class, can be an interpolation or the average, of the estimation figures related to the (sub-)classes at the MAC layer closest to the concerned (sub-)class in terms of service priority.

IV. Simulation Scenario

The proposed 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. Actually, the dynamic nature of the radio channel typically entails a higher variability in the transmission delay than that with optical or copper links.

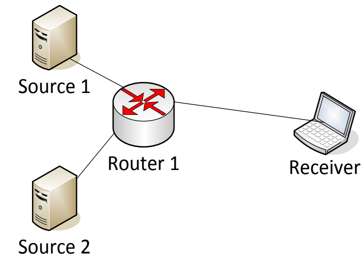

Fig. 1. Reference network scenario for the simulation analysis.

The simulation analysis has been carried out in a network scenario with two sources of traffic aggregates and one router that schedules packets supporting a PDM for QoS on output links of 54 Mbit/s (the other links are set to a higher capacity in order to be transparent - see Fig. 1). The router sends the traffic to the target receiver. Each source generates a traffic aggregate for every IP class of service. It is composed of different types of flows randomly multiplexed together, as taken by real traces [18][19]:

- 1 TCP flow backbone aggregate, which represents 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, on average, this leads to an overall traffic of more than 88 Mbit/s in each router input link.

At the IP network node, the routing and forwarding rules are as follows:

- A filter drops about 70% of the incoming traffic (in order to create a quite high load, but lower than 100%, on the issued output link), which means nearly 124 Mbit/s of the whole 176 Mbit/s. As a consequence, about 52 Mbit/s is the amount of traffic that enters in the issued interface and is sent to the receiver module;
- A classifier puts each incoming packet in the corresponding IP queue according to its DSCP value. Four AF service classes (i.e. associated with the PHBs AF1, AF2, AF3 and AF4) are instantiated, with three sub-classes each. For example, the PHB AF1 provides the sub-classes based on AF11, AF12 and AF13 [16]. 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 (priority 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 estimation process for each service class, updating 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 (based on) AF1, AF2, AF3 and AF4, respectively. According to the PDM, the granted delay by the first class should be about a half of the delay by the second class and a third of the delay by the third one. The granted delay by the second class should be about a half of the delay by the fourth one, and so on. At network layer, 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 delay differentiation for the corresponding traffic aggregates is applied at the lower layers.

Modelling an IEEE 802.11g access network, OMNeT++ simulation setup and MAC layer scheduling similar to the ones presented in [9] for scalable video (SVC) were used. Instead of enabling the prioritizing multi-queue scheduling dynamically according to the link conditions as in [9], the three queue scheduling was constantly employed. In the IEEE 802.11g delay simulations, a link with one three-layer SVC video was considered, where the base layer was treated as high priority, the first quality enhancement layer as medium priority, and the second quality enhancement layer as low priority. The link was congested by background traffic, which was put to the low priority queue. For the video packets, the MAC scheduler imposed tolerated queuing delays (4, 6 and 8 ms, for the base, first enhancement and second enhancement layers, respectively). This means that video packets are discarded if the related acceptable delay is exceeded [9]. While, background traffic is transmitted when there is no risk of not respecting the tolerated bounds for the scalable coded video packets. The physical layer used a Quadrature Phase Shift Keying (QPSK) modulation scheme with the Forward Error Correction (FEC), rate of ¾. The signal strength was set to be relatively strong throughout the simulation run, entailing only one period with retransmissions, which caused the transmission delays to grow. However, no packet losses were observed.

TABLE I. CLASS MAPPING AND LOWER LAYERS MEAN DELAYS.

MAC queue	**Mapped AF (sub-)classes (x=1,2,3,4)**	**Mean [ms]**
High priority	AFx1	5
Medium priority	AFx2	6
Low priority	AFx3	8

The mapping of the mean delay values for the video packets obtained in the IEEE 802.11g simulations to the respective network service classes is reported in TABLE I. Such values combine both the MAC queuing and actual transmission delays.

In the IP-level scheduler simulations, a MAC and PHY layer black box is leveraged, and the figures of the lower layers delay are taken by the traces (one for each data-link service class) recorded during the IEEE 802.11g simulations.

As also specified in TABLE I, the IP packets related to interactive and streaming videos are put into the high and medium priority categories, respectively. While, the background traffic composed by both video and data flows is inserted into the low priority category. Therefore, the packets of the TCP-based video flows would be assigned with the same priority as the packets of the second enhancement layer of a scalable coded video.

V. 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 options and configuration settings. The evaluation has been carried out in the OMNeT++ 4.0 simulation environment [22].

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 reliably 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 sources generate the traffic aggregates as specified in the previous section from the start of the simulation, while the results are collected after the end of the initial transitory period of 5 s.

The scalar figures are the results of an averaging process performed over values gathered with several simulation runs, where each run uses a different properly selected seed [23].

Furthermore, for each MAC service class the granted delays are pre-generated (as pointed out in the previous section), stored and read from the same trace when comparing the cross-layer and the classical approaches in order to perform a more consistent analysis.

The parameter K of the moving average (as defined in Subsect. III.B) is set to 10 for every IEEE 802.11g service priority category. It is a good trade-off between a reliable short-term estimation of the lower layers delay (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 details about the system robustness in the second part of this section). To be noted that a good choice for the value of K should consider more the channel dynamism rather than the type of traffic to be transmitted.

To better highlight the benefits of the proposed solution, a comparison with the classical approach wherein the IP and lower layers work in isolation (i.e. the AWTP scheduler determines the packet service priority without considering the current MAC and PHY performance, as in eq. (1) with $MACMA_j(t)$ set to 0) is made. Actually, there are no other alternative cross-layer optimization solutions addressing the same issue in literature to make a comparison with.

Fig. 2 and Fig. 3 depict the mean delay at the interface on the whole deploying the proposed cross-layer scheduler and the classical approach, respectively. TABLE II reports the mutual ratio of the mean delays at the interface between some of the service (sub-)classes with either the novel or the classical approach.

Looking at the collected results, it can be clearly seen how the proposed solution is able to fairly differentiate the classes of service according to the ideal target defined by the mutual ratio between the corresponding QFs.

Such a good performance is more evident when making a comparison with the classical approach. Actually, in that case the delays at the interface for the 12 (sub-)classes of the 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 IEEE 802.11g 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 is not verified), and not considered in the service priority calculation by the classical AWTP scheduler at the IP layer.

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

Simulation results collected by employing a low-pass filter for the delay estimation (see Subsect. III.B) have shown similar performance with a pole P in the range 0.90-0.99.

It is to be underlined that the proposed solution can provide better performance when the overall IP queuing delay is higher than those of the lower layers. In this case, the cross-layer scheduler can better compensate the MAC and PHY latencies, increasingly differentiating the service classes at the network level in order to support the PDM at the interface on the whole in a more reliable way (i.e. with the delay ratios for the service classes that can be very close to the ideal differentiation target).

Moreover, improvements with respect to the classical approach are more and more significant as the lower layers delay

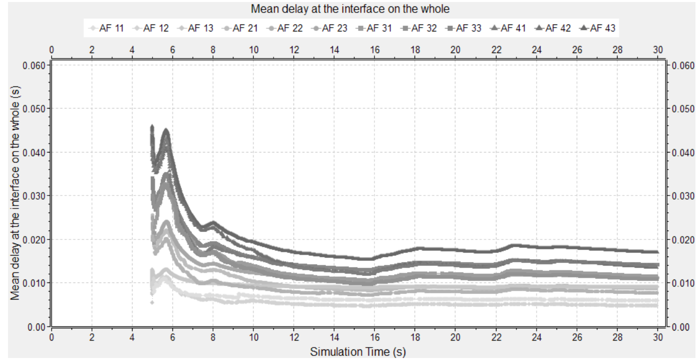

Fig. 2. Mean delay at the interface on the whole with the cross-layer solution.

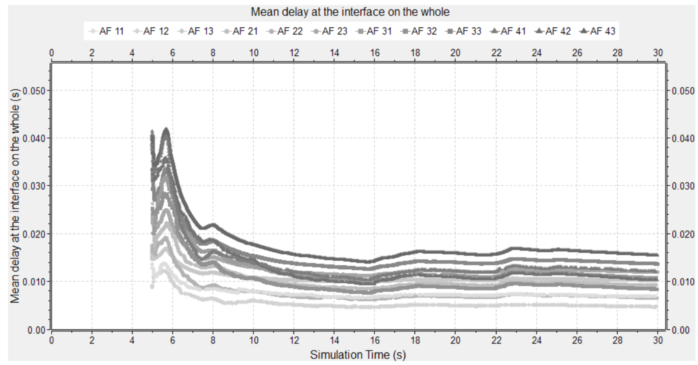

Fig. 3. Mean delay at the interface on the whole with the classical solution.

TABLE II. 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	No CL
1/1	1	1
2/1	1,44	1,32
3/1	1,91	1,55
4/1	2,29	1,74

increases (i.e. less negligible). Indeed, small delays at the MAC and PHY layers have been considered in the present simulation analysis on purpose, in order to highlight the benefits of the proposed solution even in such cases.

Further investigations aim 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 and radio channel behavior variations.

Considering that the cross-layer scheduler can inherently well support the PDM in high load conditions, even with extremely bursty traffic [7], only the latter case is worth studying. For the purpose, a new setting for the signal strength (implying packet re-transmissions) changing along the simulation run is configured.

The analysis of collected results demonstrates the reliability of the proposed solution and its better performance with respect to the classical approach in supporting a PDM also in the case of a higher variability of the lower layers delay.

Regarding the variance of the delay introduced at the router interface on the whole, the proposed IP cross-layer scheduler actually tries to balance the increasing (also decreasing) lower layers delays for a given service class. Specifically, it grants 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 objective of well respecting the proportional delay differentiation between the classes specified by the mutual ratio of the (pre-)assigned QFs. In practice, this leads to a reduced variability on the delays considering (separately) all the service (sub-)classes at the router interface.

As a general but yet prominent 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 related to a single AF PHB (e.g. corresponding to AF11, AF12 and AF13 of AF1). For an improved QoE, IP (sub-)classes associated with the same AF PHB could be mapped onto different MAC queues [9][13] (as also applied in the reported 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 operational case where the proposed solution demonstrates even more its superiority with respect to a classical approach. Actually, when the network and lower layers work independently, 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 related to the said AF PHB, while possibly experiencing largely different delays at the lower layers (compromising in this way the reliable support of a PDM at the interface on the whole).

VI. Conclusions

This work provides a solution for the 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 supported considering the performance of the interface on the whole. The novel fundamental principle is to determine the service priority for a Head of Line (HoL) packet in an AF sub-class (e.g. related to either AF11, AF12 or AF13 for AF1 PHB) taking into account also the expected delay at the MAC and PHY levels for the traffic of that (sub-)class. For the purpose, cross-layer signaling is employed. Specifically, the in-band DiffServ Code-Point (DSCP) is leveraged from the network to the lower layers (for a consistent classification and queuing), while delay feedbacks flow in the opposite direction. The cross-optimization ensures reliability and robustness also in case of extremely time-variant performance, which is typical of wireless networks. On the other hand, the classical approach for IP QoS, where the network and lower layers work independently, shows serious limitations when the MAC and PHY levels are not transparent. In this respect, the designed solution could be deployed in the critical points of the network (e.g. on the access wireless interfaces) only as for an improved backward compatibility. A possible fully software-based implementation and the applicability to a large variety of different access network technologies, mechanisms and policies promotes the benefits of our proposal.

The designed solution was evaluated through simulation analysis. The results show that the delays granted to the instantiated (sub-)classes of service are fairly 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 highly varying lower layer performance. The PDM for QoS is reliably supported also in the critical scenario when the sub-classes associated with the same AF PHB are mapped onto different MAC classes, and hence queues. While, the classical approach is observed to be definitely unsuitable when the MAC and PHY layers delays are not negligible with respect to the IP-level delays.

Future work regards the performance analysis of the proposed solution with an integrated and detailed modelling of the transmission technology (e.g. 3GPP LTE-A, IEEE 802.11) in given radio channel conditions (e.g. slow or fast fading, interference level, signal strength) changing over time, and with a good variety of lower layers scheduling and queuing management policy. Last but not least, a new cross-layer optimization of the AWTP scheduler can be designed leveraging some sort of simple feedback from lower layers about the current performance, possibly including delay correlations.

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