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Cross-layer Scheduling with Feedback for QoS Support

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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, considering the dynamic nature of radio channels typically, it is difficult to achieve a given service provisioning working at the IP and lower layers separately as in the classical approach, without a run-time adaptation of the system towards the target quality. This work describes an IP cross-layer scheduler able to support a Proportional Differentiation Model (PDM) for delay guarantees with content-awareness, also over wireless. 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 service classes in a closed-loop control with the objective of supporting a PDM at the network node on the whole, considering the cumulative latency in crossing the first three layers of the protocol stack, as relevant for the end-user. A simulation analysis demonstrates the prominent improvements in reliability and robustness of the proposal in the case of time-variant performance of the MAC and PHY layers with respect to the classical non-cross-layer approach and the open-loop control. Furthermore, considerations on the required functionality and likely deployment scenarios highlight the scalability and backward compatibility of the designed solution in supporting the concept of network transparency for the delivering of critical applications, as of the e-health domain.

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1. Introduction

Next-Generation Network (NGN) [1], is an IP network with Quality of Service (QoS) support and able to efficiently transport heterogeneous traffic. ITU Standards G.1010, Y.1541 and Y.1221, as summarized in [2],

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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.

IETF Differentiated Services (DiffServ) [3] can provide different levels of service 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 supporting quality guarantees out of the core and into the edges of the network, where it could be feasible to maintain a restricted amount of per-flow state.

Roughly speaking, the proposals available in literature for providing QoS can follow either an absolute or a relative approach for DiffServ [5]. The former aims to provide QoS in absolute terms 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. Therefore, service provisioning according to the content to be delivered is enabled by both the approaches, supporting the concept of network transparency, as required by the innovative and critical (multimedia) applications, as of the e-health domain.

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 used with multimedia applications, which in some cases can even adapt to variations in network performance (e.g. AV conferencing, AV streaming and mission critical applications). 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 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, as the cumulative latency in crossing them is relevant for the end-user. In detail, it can provide a delay differentiation between the instantiated IP service classes according to the mutual ratio of (pre-)assigned quality factors, taking into account the overall latency in crossing the IP, MAC and PHY strata by packets before being transmitted. It leverages feedbacks about the lower layers delay with a closed-loop control.

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, as well as supporting service differentiation for the content to be delivered. Indeed, a proportional model for QoS is followed 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 critical (i.e. extremely time-variant lower layers 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).

Noticeably, the consistent support of a PDM with enough resource provisioning, enables lossless or almost lossless transfer at low delay. Therefore, it realizes the concept of network transparency, as required by the critical applications of the e-health domain, for example. Indeed, prompt and correct diagnoses require the flawless transmission of medical data, images and videos.

The remainder of the paper is organized as follows. In Sect. 2, the state-of-the-art about supporting a PDM with the open issues is reported. In Sect. 3, there is a brief overview of the feedback control theory and how it can be applied to the QoS management in NGNs (i.e. over heterogeneous technologies, both wired and wireless). In Sect. 4, the proposed IP cross-layer scheduler is presented. Sect. 5 describes the investigated simulation scenarios, while Sect. 6 discusses the collected results, making also a comparison with the classical approach, wherein the layers work in isolation, and the open-loop control of the actual service differentiation. Finally, Sect. 7 outlines the main conclusions and future developments.

2. PDM support and Open Issues

Proportional Differentiation Model (PDM) [5] for QoS yet allows for controllability, consistency, efficient resource exploitation and scalability. There are several solutions that successfully leverage this model at IP layer to enforce proportional average delay or packet loss ([5] and [6], for example). Specifically, (Advanced) Waiting Time Priority ((A)WTP) schedulers [7] can approximate the proportional delay differentiation model also in short timescales.

However, inconsistencies can arise in the 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 ones) in order to give priority to the critical traffic [8], even differently within a single flow [9].

However, the time-variant performance of the radio channel still entails unpredictable (and not negligible) delays with the result that the service proportionality between the classes as configured at the IP layer can be seriously compromised [10]. 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 [10][11]. 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. [12] is an 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 robustness of the resulting PDM implementation.

Ref. [10] defines a general framework in which IP, MAC and PHY layers are considered on the whole from the prospective of the packet scheduling. Indeed, the proposed IP scheduler leverages feedbacks about the delay experienced at the lower layers to tune at run-time the packet service priority by an AWTP-like algorithm in order to consistently support a PDM. Even if this solution can achieve a significantly better delay differentiation at the interface on the whole than with the classical approach, the obtained mutual ratios of the cumulative delays still not equal the mutual ratios of the quality factors assigned to the IP service classes. Furthermore, the inherent limitations of the employed scheduling discipline [7] appear more and more with an increasing number of supported service classes and decreasing of the average load on the issued interface, even with roughly constant traffic levels.

3. Principles of feedback control theory

The feedback control theory [13] is widely used in various dynamic systems, in which phenomena occur over time domain. The feedback is the capacity of the dynamic system to take care of the system output with some elaboration (by the controller) to modify the features and behaviour of the system itself, acting on the system input.

Feedback control theory has been recently applied in computer science to design resource scheduling applications, as for wireless networking and bandwidth management ([14 -16]), in order to achieve the desired performance.

A Proportional Integral Derivative (PID) controller [17] is a feedback control mechanism that calculates an "error" as a difference between a measured process variable and a target set point. Then the (closed-loop) controller attempts to minimize such an error operating on the issued process input. The PID controller algorithm includes three contributions: P, which represents (a multiple of) the current value of the error signal, I, which considers the integral of the past values of the error signal and D, which is proportional to the current variation of the error signal.

Ref. [18] is a first attempt to exploit the closed-loop control for QoS management in an all-IP wired and IEEE 802.11 wireless network. The system aims to address an efficient bandwidth resource usage in a delay-constrained environment, in order to efficiently meet dynamic QoS requirements for real-time traffic. This is operated employing a PID controller that estimates the traffic bandwidth requirements considering the current network conditions using a threshold-based algorithm. However, this pioneering solution is focused on a QoS MAC scheduler, in which the closed-loop control neither exploits any cross-layer information, nor considers the IP layer.

4. Proposed solution

The main objective of this work is to design a cross-layer scheduler at the common IP layer that is able to provide a delay differentiation between service classes according to the mutual ratios of (pre-)assigned Quality Factors (QFs) at IP level, considering the cumulative latency (as relevant for the end-user) in crossing the IP, MAC and PHY layers by packets before being transmitted. Specifically, the error with respect to the ideal values of the said mutual ratios is minimized leveraging a feedback (i.e. closed-loop) control. The solution should be flexible enough to be applied to different (wired and) wireless technologies (i.e. 802.11, LTE or WiMAX), channel conditions and nodes settings. Besides, content-aware delivery is achieved by differently sorting out application data onto the available service classes, which can provide lossless or almost lossless transfer at low delay (with a proper resource provisioning and buffer dimensioning), addressing the concept of network transparency. This should foster the introduction of innovative and critical applications, as of the e-health domain. Indeed, prompt and correct diagnoses require the flawless transmission of medical data, images and videos.

In order to take into account the current lower layers behaviour and performance, the proposed scheduling algorithm needs to be dynamic in nature. In other words, its configuration and operating parameters are necessarily to be tuned run-time. Cross-layer communication, (closed-loop) adaptation and optimization are required.

More precisely, feedbacks coming from MAC and PHY levels, which can be referred to a wireless interface as the most critical case, should provide information about the run-time transmission performance. Such feedbacks can be used not only to build either an analytical or a statistical model of the lower layers behaviour, but also to apply a closed-loop control.

In literature [19] [20] some works describe the formalization and use of the "Effective Capacity" theory about the actual lower layer performance. 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 dealing with the likely highly time-variant nature of access and wireless links 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. However, 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.

The design of our cross-layer scheduler takes as starting point the AWTP [7]. Such a scheduler can well support a delay differentiation between classes at IP layer 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) [7]. However, the IP packet service priority is simply determined by considering the queuing delay at the network layer only.

The key difference and prominent enhancement of our proposal is that the priority of the IP packets for a given class actually 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, minimizing the error with respect to the ideal target performance by applying a closed-loop control. In practice, the 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.

The Controller uses the current and the past values of the IP and MAC delays for each service class to calculate first, the mutual ratios of these actual delays between the classes and then, the difference of such ratios from the ideal target mutual ratios as defined by the assigned quality factors. From these errors, the corrective terms (indeed, one term per class) to be applied in the service priority algorithm (as described in Subsect. 4.2) are determined.

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 service class.

For the purpose, the AF PHB [21] can be used. It provides 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, it could be applied to video streams that are coded in different frame types (i.e. I, P and B) or layers (i.e. base and enhanced) [9]. Therefore, a content-aware solution is enabled at both IP and lower layers.

In practice, the number of feedback sequences coming from the lower layers equals the number of MAC (sub-)queues. Relying on the AF PHB as in-band signaling 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 [7]. 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 concerned service class (see also Subsect. 4.3) and being triggered at every packet transmission only. The applied PI Controller (PID Controller where the D contribution is absent, to avoid stability issues [17]) enhances the proposed scheduler without introducing more complexity, since the error calculations are in number linear with the cardinality of the supported IP (sub-)classes and it acts every T sec., where T is at least an order of magnitude greater than the packet transmission time (see also the next subsection).

4.1. PI Controller error calculation

This subsection describes how the PI Controller calculates the error in order to improve the PDM support at the interface on the whole.

Let QF_j be the quality factor associated with the IP (sub-)class-*j*, $MAw_j(t)$ the moving average of the waiting time of the last K IP packets sent to the lower layers of the IP (sub-) queue-j and $MAMAC_j(t)$ the moving average of the MAC and PHY layers delay experienced by such K transmitted packets. For stability purposes, the feedback errors are built on the calculated averages, therefore by a (short-term) estimation of both IP and lower layers delays.

The error $\varepsilon_j(t)$ of the queue j is calculated as follows:

$$\frac{\left(MAw_j(t)+MAMAC_j(t)\right)+\varepsilon_j(t)}{\left(MAw_1(t)+MAMAC_1(t)\right)}=\frac{QF_j}{QF_1} \quad (1)$$

$$\varepsilon_j(t)=\frac{QF_j}{QF_1}\left(MAw_1(t)+MAMAC_1(t)\right)-\left(MAw_j(t)+MAMAC_j(t)\right) \quad (2)$$

The error is subtracted from the IP waiting time in Eq. (3), which calculates the virtual normalized waiting time of the class-*j* for the service priority determination.

Such operations are performed every T sec. The choice of T should be carefully made, because a too high error calculation frequency would introduce unnecessary computational overhead (though, the complexity of the scheduling algorithm remains linear, as discussed previously in this section), while a too low one could invalidate the effect of the closed-loop control (if not make it counterproductive, due to the dynamic nature of the issued radio channel).

4.2. 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 to be forwarded.

As in AWTP scheduler, a pseudo-service technique [7] is employed. It virtually transmits the HoL packet of each class-*i* P_i to ascertain the virtual waiting times of all HoL packets after P_i 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, $MACMA_j(t)$ the estimated value of the delay at the MAC and PHY layers for class-*j*, and $\varepsilon_j(t)$ the error that the PI Controller has calculated using Eq. (2). When the pseudo-served packet belongs to class-*i*, the proposed scheduler calculates the virtual normalized waiting time of class-j, $\widetilde{V}^i{}_j(t)$, and obtains the maximum proportion, $MP_i(t)$ as:

$$\widetilde{V}^i{}_j(t)=\frac{w_j(t)+MACMA_j(t)-\varepsilon_j(t)+X_i}{QF_j} \qquad X_i=\begin{cases}0 & if \quad i=j\\ T_i(t) & if \quad i\neq j\end{cases} \quad (3)$$

$$MP_i(t)=\max_{1\le j\le N}\widetilde{V}^i{}_j(t), \quad (4)$$

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

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

$$MMP_i(t) = \max_{1 \le i \le N} MP_i(t) \tag{5}$$

$$C(t) = \arg\max_{1 \le i \le N} MP_i(t) \tag{6}$$

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

4.3. Delay estimation process

As already pointed out, the averaging process applied to the values of the packet latency at the MAC and PHY layers 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 (actually, also at the IP layer for the feedback error calculations) for each service class (rather than a sequence of values of packet delays) as input to the designed IP scheduler (for the feedback error calculation as well) helps in reducing the introduced overhead. Additionally, the averaging process can be implemented at MAC layer directly, thus limiting the amount of data that needs to be communicated from the lower layers to the network layer. The queuing delay at MAC layer can be precisely measured; while, either the PHY or MAC layer, depending on the used access technology and configuration, can estimate the one-way transmission delay based on acknowledgements and re-transmissions, for example. Alternatively, the averaging 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 option for the filtering of the packet delays is the moving average [12], where K consecutive values of the queuing delay D_F experienced by each packet (frame) in a given queue are considered for the filter output calculation. Hence, a single operation is required at every packet transmission.

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 (likewise, for the estimation of the delay at IP layer).

5. 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 for a consistent support of a PDM, aimed at addressing the concept of network transparency. Indeed, the dynamic nature of the radio channel typically causes a higher variability in the delay experienced by packets at the lower layers than 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 Fig. 1), which deploys a PDM for QoS on output links of 100 Mbit/s (the other links are set to a higher capacity in order not to affect the collected results). 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 as taken by real traces [22][23]:

- 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, this leads to more than 88 Mbit/s on average of overall traffic in each of the two router input links.

At the router interface, operations are as follows:

- A filter drops about 45% of the incoming traffic, as for analysis purposes, corresponding to nearly 80 Mbit/s of the whole generated 176 Mbit/s (which results from having four aggregates of about 22 Mbit/s at each of the two input interfaces). As a consequence, about 98 Mbit/s is the amount of traffic that enters 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. associated with the PHBs AF1, AF2, AF3 and AF4) are supported at the network level, each with three sub-classes. For example, the AF1 PHB provides the sub-classes based on AF11, AF12 and AF13 PHBs [21]. Therefore, the total number of IP (sub-)queues (i.e. (sub-)classes) is 12;
- A server picks up packets from the IP (sub-)queues applying the proposed cross-layer scheduling algorithm with closed-loop control 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 AFij 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 MAC and PHY delay estimations available to the server for the cross-layer scheduling algorithm calculations;
- A PI Controller that calculates the errors to be used by the server in the designed scheduling algorithm, as specified in Subsect. 4.1. The errors are (re-) determined every T=100 ms using the delays (at IP and lower layers) of the last transmitted K=20 packets (as for a good trade-off between achieved performance and stability, i.e. between reliability and robustness).

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 PHBs, 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. the sub-queues related to 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.

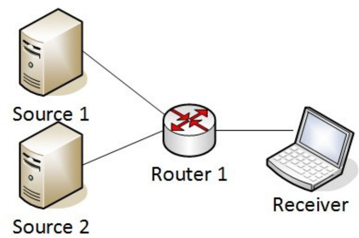

Fig. 1. Reference network scenario for the simulation analysis.

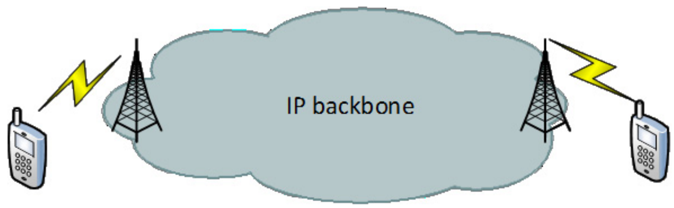

Fig. 2. Network scenario considered for the LTE single hop maximum delay evaluation

As reported in Eq. (2), the error calculation uses the delay of the packets belonging to the first IP service class (i.e. based on AF1 PHB) as reference in the ratios determination. However, such a class is made up of three sub-classes. Therefore, it is necessary to specify which values are actually used. Three different options are considered: the average delay in the three sub-classes, the delay in the best sub-class (i.e. related to AF11 PHB) and the delay in the worst one (i.e. related to AF13 PHB).

Without loss of validity and generality for the performed analysis, the MAC and PHY layers are modelled as a black box, providing QoS guarantees as in an LTE network [24]. The LTE classes of service with Quality Class Identifier (QCI) 7, 4 and 8 are loaded with the traffic from the (sub-)classes associated with AFx1, AFx2 and AFx3 PHBs (with x=1, 2, 3 and 4), respectively (while, there is no traffic in the other LTE classes). As by standard [25], the packet delay budget for them is 100, 150 and 300 ms, respectively. Consistently with the standard, the TCP traffic has been assigned with the AFX3 PHBs, the MPEG video streaming traffic with the AFx PHBs2 and the MPEG video conference traffic with the AFx1 PHBs (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 Dm. In mobile wireless systems, the radio channel delay statistical distribution is affected by 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 Nt (a Normal distribution where only the positive values are extracted) is configured for the presented results. Without loss of generality for evaluation purposes, Nt is taken as an instance that should match the actual delay distribution. In a network scenario where two user terminals communicate through an IP backbone (see Fig. 2), half of the maximum end-to-end delay (i.e. the delay budget) $D_m/2$ can be 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 for a normal distribution 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 hereafter 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.

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

6. 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 by OMNET 4.0 [26], as a reliable and popular open-source simulation tool.

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 latency experienced by packets at the network and lower layers).

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 scalar figures are the result of an averaging process performed over values gathered with several simulation runs, using each a different seed properly selected [27]. Furthermore, for each MAC service class the granted delays are pre-generated, stored and read from the same trace when comparing the cross-layer scheduler either with or without the closed-loop control, in order to perform a more consistent analysis. This is also applied when comparing the cross-layer scheduler in closed-loop control with the former classical non-cross-layer version of the AWTP scheduler. Indeed, the discussions provided in this section point out the benefits of the novel scheduler with respect to both the well-consolidated classical approach and the most performing solution available in literature [10] to support a PDM at the interface on the whole (where a cross-layer AWTP scheduler has been proposed in open-loop).

The parameter K of the moving average (as named in Subsect. 4.3) is set to 10 (for every traffic aggregate, at either IP or LTE MAC layer), being a good trade-off between having a reliable estimation of the lower layers delay (and IP one, as well) in the short-term (which in turn leads to an higher adaptation capacity of the designed cross-layer scheduler) and stability of the system in spite of quick and possibly impulsive, changes in the radio channel performance (see also the considerations about the system robustness in the second part of this section).

Due to limited space availability, the results about better performance of the novel closed-loop cross-layer scheduler with respect to the open-loop version of Ref. [10] in not heavy average traffic load conditions and higher number of supported IP classes for an enlarged service differentiation are not reported. As already mentioned in Sect. 2, in such a scenario also the latter scheduler presents decreased performance as inherited by the former AWTP scheduling discipline [7]. It is intuitive that a feedback control can improve the service differentiation (i.e. making it more similar to the ideal mutual ratios of the assigned quality factors) more strongly when a poorer differentiation is provided in an open-loop operating mode. Therefore, the following analysis focuses on network and traffic scenarios to be considered more in depth in order to highlight the benefits of the closed-loop control applied to the cross-layer scheduler proposed in [10], which already demonstrate a significant improvement with respect to the classical approach.

The reliability of the proposed solution is first evaluated. Fig. 3 and Fig. 4 depict the mean delay at the interface on the whole deploying the former AWTP scheduler and the designed cross-layer scheduler in closed-loop, respectively. Table 2 reports the mutual ratios of the mean delays at the interface on the whole between the first (sub-)classes of service related to each AF PHB for the cross-layer scheduler in open-loop and closed-loop. This have been carried out for three different options of taking as reference the AF1 PHB service (sub-)classes for the error calculations, either considering the average delay experienced in all of them (based on AF11, AF12 and AF13 PHBs), or in the best (sub-)class (based on AF11 PHB), or in the worst (sub-)class (based on AF13 PHB). However, only the values for the most performing case of using the best (sub-)class related to AF11 PHB is shown. For the sake of completeness, the corresponding mutual ratios with the classical non-cross-layer approach are included as well.

Table 2. Mutual ratios of the average delays at the interface on the whole for some of the (sub-)classes of service (related to AF11, AF21, AF31 and AF41 PHBs) for the classical non-cross-layer AWTP (No CL), the cross-layer scheduler in open-loop and the novel cross-layer scheduler in closed-loop.

Service Class	QFs ratio	Mutual ratios		
		No CL	CL in open-loop	CL in closed-loop
AF11	1/1	1.00	1.00	1.00
AF21	2/1	1.32	1.82	2.11
AF31	3/1	1.67	2.68	3.13
AF41	4/1	1.95	3.42	4.04

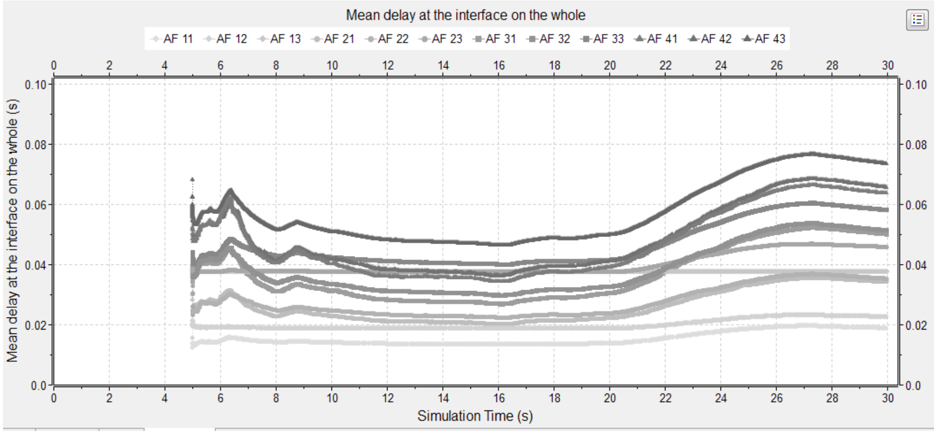

Fig. 3. Mean delays at the interface on the whole with the former AWTP scheduler.

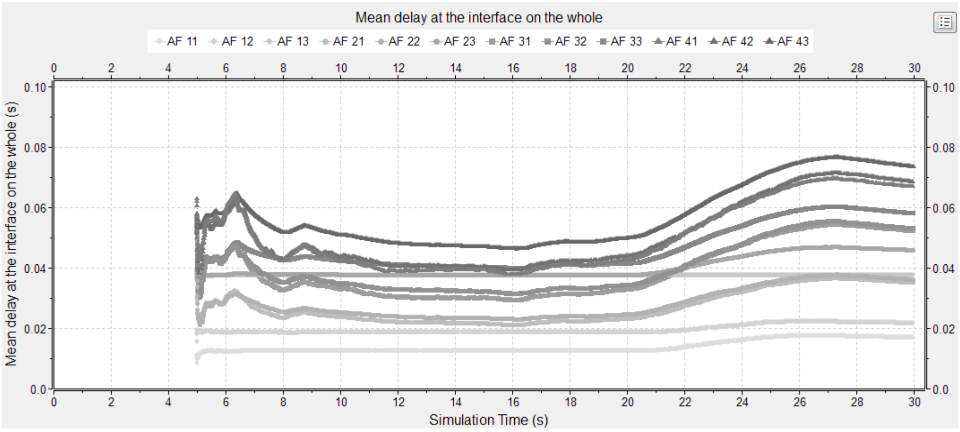

Fig. 4. Mean delays at the interface on the whole with the novel cross-layer scheduler in closed-loop.

Looking at the collected results, it can be seen how the proposed solution is able to better differentiate the classes of service according to the mutual ratio between the corresponding QFs with respect to both the former AWTP scheduler and the cross-layer scheduler in open-loop. noticeably, while the former AWTP scheduler cannot support a PDM at the interface on the whole (see also Ref. [10]) because the lower layers delay is not negligible and not considered at the IP layer in the classical approach, in both the cross-layer versions of the said scheduler the curves of the average delays for the 12 supported IP (sub-)classes of service are consistently subdivided into 4 groups (i.e. the number of deployed AF PHBs). This is true even when the traffic of a DiffServ aggregate is mapped onto different quality categories at the lower layers as in the present analysis. Providing further quantitative figures, the mean delay at the interface on the whole granted by the service (sub-)classes based on AF11, AF21, AF31 and AF41 PHBs is respectively 18.41, 24.39, 30.78 and 35.98 ms with the classical approach. While, the mean delay with the cross-layer scheduler in open-loop for the same classes is 18.19, 33.20, 48.68 and 62.23 ms, respectively. Finally, the mean delay with the cross-layer scheduler in closed-loop for the same classes is 16.25, 34.21, 50.88 and 65.63 ms, respectively. It is apparent as the average delay of 12.50 ms experienced at the lower layers in the considered service classes (refer to Table 1) is not compensated in the classical approach, and the novel scheduler achieves the best service differentiation.

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 is also considered. Mainly, two possible cases of environment change can be envisaged: traffic or radio channel behaviour variations.

Taking into account that the cross-layer scheduler can inherently better support a PDM more and more with increasing load conditions, [7], 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. However, the maximum acceptable delay at the wireless interface is still kept as by LTE standard (see Sect. 5). The analysis of collected results demonstrates that the proposed IP cross-layer scheduler with the closed-loop control is able to better honour a PDM also in the case of higher variability of the lower layers delay (i.e. more robust than the cross-layer scheduler in open-loop presented in Ref. [10], where poor results about the classical approach for the analysed scenario are also reported).

7. Conclusions

This paper presents a solution with feedback control for the support of a Proportional Differentiation Model (PDM) for QoS with content-awareness in NGNs, leveraging cross-layer communication and optimization strategies over 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 performance at the interface on the whole, as relevant for the QoE of the end-user. Noticeably, the consistent support of a PDM with enough resource provisioning, enables lossless or almost lossless transfer at low delay. Therefore, it realizes the concept of network transparency, as required by the critical applications of the e-health domain, for example.

The key idea is to determine the service priority for a Head of Line (HoL) packet in an AF (sub-)class (e.g. related to either AF11 or AF12 or AF13 for the AF1 PHB) taking into account the expected delay at the MAC and PHY levels (provided as cross-layer feedbacks) for the traffic of that (sub-)class. Reliability and robustness are improved by a closed-loop control leveraging the error between the target ideal mutual ratios of the assigned QFs and the current mutual ratios of the average delays in the service classes.

The novel scheduler ensures higher reliability and robustness with respect to the available solutions addressing the support of a PDM for QoS. The classical non-cross-layer approach appears inadequate when the MAC and PHY levels are not transparent. While, the open-loop cross-layer scheduler proposed in Ref. [10] has some limitations in given traffic and network scenarios, as inherited by the former AWTP scheduling discipline, and proven to be less performing in the investigated simulation scenarios.

Interestingly, the designed solution could be deployed in critical points of the network (e.g. on the more dynamic 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.

Future work regards the performance analysis of the proposed solution with a detailed modelling of a given transmission technology (e.g. LTE or Wi-Fi) in specific radio channel conditions (e.g. slow or fast fading, interference level, SNR value) changing over time. Furthermore, different feedback control and filtering process for the lower layers delays estimations, together with the related operating parameters, can be also designed and investigated for an improved reliability and robustness.

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