Performance comparison of scheduling algorithms for multimedia traffic over High–rate WPANs

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***Abstract*—The IEEE 802.15.3 standard aims at covering the gaps of current WPAN technologies in supporting applications with very high–rate and/or quality of service requirements. To this end, the standard encompasses high–rate modulations and a flexible medium access mechanism, which permits resource reservation. Although the standard specifies the general framework for defining resource reservation mechanisms, the actual implementation details of scheduling algorithms is left open to proprietary solutions.**

In this paper we investigate the potentialities offered by IEEE 802.15.3 framework for supporting multimedia services. More specifically, we analyze the performance of some classical scheduling policies in presence of intensive real–time and multimedia traffic, in order to identify the most effective strategy for the considered scenarios.

The analysis has been performed by using a complete 802.15.3 C++ simulator, where we have realized the different scheduling strategies upon an entirely standard–compliant round robin polling procedure. Results show that, in most cases, EDF approach offers better performance, though its margin with respect to the other strategies strictly depends on the specific scenario considered.

***Index Terms*—Multimedia, high rate WPAN, quality of service, resource management, scheduling**

I. Introduction

THe standardization effort of the IEEE 802.15.3 group is intended to provide High–Rate Wireless Personal Area Network (HR–WPAN) technologies for supporting the always growing demand for mobile connectivity, easy data sharing and inter–operability among electronic devices of different nature. In particular, WPAN technologies are expected to permit wireless fruition of multimedia services, such as video streaming, voice over IP, multi–player gaming, which have been experimenting an impressive diffusion in the last years. The realization of the envisioned scenario requires the definition of suitable radio resource management schemes, able to provide each application with the required Quality of Service (QoS) level [1]. Resource sharing is a classical and well–known problem, which has been addressed in several different contexts, leading to the definition of many scheduling algorithms of different complexity.

In this paper, we address the problem of supporting heterogeneous multimedia flows, such as in MPEG-4 video, Voice over IP, and interactive gaming, in HR-WPANs, from a practical perspective. Instead of searching novel scheduling schemes, whose complexity often overtakes the performance benefits, we focus our attention on classical, well established algorithms, extensively tested in other scenarios, that might be readily ported on this novel networking platform. More specifically, we compare four well–known scheduling algorithms, namely Generalized Processor Sharing (GPS), Earliest Deadline First (EDF), EDF with Discard (EDF–DS) and EDF with Soft/Hard deadlines (EDF–SH), in terms of Job Failure Rate, in different application scenarios. To this end, we define a standard–compliant polling mechanism that permits the network coordinator to gather the traffic information from the source devices and schedule the transmission resources as dictated by the considered scheduling algorithm.

The rest of the paper is organized as follows. Section II reviews the literature on the topic. Section III briefly overviews the 802.15.3 standard, with particular attention to the Medium Access Control (MAC) scheme. The traffic models employed in the study are described in Section IV. Section V presents the polling procedure we propose to collect traffic information from the devices. Section VI describes the scheduling algorithms adopted in the work. Simulation results are presented and discussed in Section VII. Finally, Section VIII concludes the paper with some final considerations.

II. Prior art

Prior work on this area is rather scarce. To begin with, [2] proposes a rate adaptation mechanism for HR WPAN, whereas a scheme to recover the bandwidth waste due to imperfect scheduling is presented in [3].

The issue of managing different priority traffic classes in saturated networks is considered in [4]. More specifically, the authors focus on a scenario where transmission resources are statically assigned to traffic flows, upon request. According to the standard resource management policy encompassed by IEEE 802.15.3 specs [5], a request that exceeds the amount of available resources is rejected, irrespective of its priority class. Therefore, a high priority flow request might be delayed because transmission resources are fully occupied by lower priority flows. To alleviate such a problem, [4] proposes a novel scheduling scheme that reduces the access delay of high priority flows by ”stealing” some transmission resources from lower priority flows. In this manner, the system is able to provide fast channel access to high priority flows at the cost of slowing down the service offered to lower priority flows.

The throughput maximization and delay minimization in HR WPAN is addressed in [6], where a scheme to manage multimedia traffic at MAC layer is presented. The basic idea is to balance the amount of resources dedicated to contention–based

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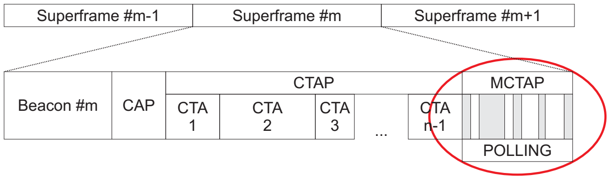

Figure 1. General superframe structure.

and contention–free access, according to the overall offered traffic. In fact, contention–based access is more efficient under light traffic loads, whereas contention–free access becomes preferable when the traffic load increases.

These works refer to scenarios with traffic belonging to different priority classes, but they do not specify nor consider the actual nature of the traffic. A step forward in this direction is made in [7], where the authors explicitely address the problem of transmitting MPEG–4 coded video flows over a high rate WPAN. A MPEG–4 traffic flow, which is described in greater detail in Section IV, consists of a stream of packets of different type and size, emitted according to a given pattern. Generally, the resources needed to sustain a MPEG–4 flow are uniformly allocated in time, irrespective of the way the video traffic is produced. This may lead to suboptimal performance, due to the variable bit rate nature of the traffic source. Hence, in [7] a resource allocation that resembles the typical pattern of a MPEG–4 source is proposed. However, to reach optimal performance, the scheme needs to know in advance the characteristics of the MPEG–4 flow (as the maximum packet size for each packet type): imperfect knowledge yields to performance loss. Moreover, a portion of the allocated bandwith remains unused any time the transmitted packet is smaller than its maximum expected size.

Another solution for providing quality of service (QoS) in WPAN is presented in [8], where authors resort to traditional control feedback theory for controlling the backlog of the different flows. Transmission resource is, then, allocated in order to stabilize the queue length of each flow around a desired target value that is related to the required QoS. This approach, however, may lead to inefficient resource usage in heterogeneous scenarios, when traffic flows with different QoS requirements coexist.

III. IEEE 802.15.3 BASICS

The 802.15.3 standard defines a Wireless Personal Area Network (WPAN) with a limited spatial extension, able to support high data rates (ranging from 11 up to 55 Mbps) and QoS oriented [5].

The network topology of IEEE 802.15.3 closely resembles Bluetooth's one: the HR–WPAN is called *piconet* and it is composed by a set of *devices*, denoted by *DEV*, logically associated to a *piconet coordinator*, indicated by *PNC*. The PNC controls and manages the piconet functioning through the periodic broadcasting of an informative *beacon* message.

Every beacon begins a time interval, named *superframe*, of variable duration (up to 65535 μs). The beacon is usually followed by a Contention Access Period (CAP) that, in turn, is followed by a Channel Time Allocation Period (CTAP). During CAP, channel access is governed by the usual Carrier–Sense Multiple Access – Collision Avoidance (CSMA/CA) protocol, whereas during CTAP a collision–free Time Division Multiple Access (TDMA) scheme is adopted. More specifically, the CTAP is arranged in uneven time slots, called Channel Time Allocations (CTAs) and Management Channel Time Allocations (MCTAs). The general superframe structure is graphically illustrated in Fig. 1.

CTAs are univocally assigned to a communication flow identified by the triplet {*stream ID, source DEV, destination DEV*} and they can be either static or dynamic. A static CTA occupies a fixed position within each superframe and has constant time duration, whereas position and time duration of dynamic CTAs can be changed on a superframe-by-superframe basis, according to the scheduling policy implemented by the PNC.

Management–CTAs (MCTAs) share the same structure of CTAs, with the difference that they are dedicated to communication between PNC and DEVs, i.e., DEV–to–DEV communication cannot occur in MCTAs. The standard encompasses three types of MCTAs, namely *regular*, *association*, and *public*. Regular MCTAs are univocally assigned to specific DEVs and can be used for different purposes, such as exchanging control information with the PNC in a collision–free manner. Association and public MCTAs, instead, are not reserved and can be accessed by using a slotted ALOHA procedure. Such slots are used to exchange generic control messages, as CTA allocation, association and disassociation requests.

The subdivision of the frame in CAP and CTAP, and the assignment of CTAs and MCTAs to the different DEVs, is univocally determined by the PNC on the basis of the amount of resources requested by each DEV in the piconet. Although the standard defines the basic mechanisms that permits the exchange of information between PNC and DEV, it does not specify how the info exchange shall be realized, nor the way such an information has to be used.

The collision–based access mechanism used in CAP is not suitable for supporting intense multimedia traffic, as also noticed in [4], [6], [7]. Hence, in this paper we focus on the CTAP period only.

IV. MULTIMEDIA TRAFFIC MODELS

Multimedia traffic is usually subject to delay constraints, i.e., packets generated by the multimedia source shall be delivered to the remote peer within a given delay bound, for the quality of service to be preserved. A general distinction can be made between *Hard–QoS applications*, which suffer strong quality degradation in case of delay–bound violation, and *Soft–QoS applications*, which show progressive service degradation as the delay increases over the *soft* deadline. In addition, Soft–QoS applications can be associated to a second *hard* deadline, after which packet delivery is useless.

In this work, we consider both Hard– and Soft–QoS sources, in the effort to compare the scheduling algorithms in a challenging and realistic scenario. More specifically, we consider MPEG–4, Voice over IP and interactive–gaming traffic flows, as specified in the following.

A. Audio Video Traffic (MPEG–4)

MPEG–4 is an efficient and highly scalable encoding format for audio/video streaming. For a detailed description of the codec, which is out of the scope of this paper, we refer to [9] from which we have also taken the following traffic model, used to simulate the MPEG–4 sources:

- hard QoS requirements (hard deadline: $40\,ms$);
- constant frame rate: 25 fps;
- average bit rate: 1.1 Mbps;
- *simulated transport protocol: UDP.*

B. Voice Over IP Traffic (VoIP)

In this work, we consider $G.723.1$ high bit rate voice encoders, which generate packets of 24 bytes every $30\,ms$. Each packet, however, goes through RTP, UDP and IP protocol layers before reaching the 802.15.3 MAC layer, so that the packet size to be transmitted is 40 byte longer than what originated by the codec. To simulate the typical speech–silence pattern of voice concersations, we adopted the classical ON–OFF Markov model defined in [10], with ON and OFF periods of $352\,ms$ and $650\,ms$, respectively. The VoIP model is, hence, summarized as follows:

- hard–QoS requirements (hard deadline: $100\,ms$);
- Markovian on/off model (voice activity/silence);
- constant packet rate (CBR) during ON periods: ~ 33 fps;
- average bit rate: < 20 kbps;
- *simulated transport protocol: RTP.*

C. Interactive Gaming Traffic (i–gaming)

Another class of applications that is expected to become very popular in the WPAN community is Interactive Gaming (i–gaming). I–gaming is a good example of soft QoS applications: when packet delay exceeds a soft deadline, the user experience smoothly degrades with the increasing of the packet delivery delay, up to a threshold (corresponding to the Hard Deadline) beyond which the session will likely be aborted by the player.

I–gaming traffic is determined by a number of factors, such as software differences, number of participants per session (from few to hundreds), geographical distribution of participants, network conditions, and so on. To capture such aspects, we have proceeded to direct inspection of long sequences of traffic generated by a First Person Shooter, with tight delay and rate bounds.[1] From the data collected, we have observed that the empirical statistical distribution of the packet size and inter–arrival time could be fairly well matched by Gamma and Rayleigh distributions, respectively, with parameters as in Tab. I.

In summary, i–gaming traffic model has been characterized as follows:

- Soft QoS requirements (Soft Deadline: $15\,ms$, Hard Deadline: $30\,ms$)
- variable packet rate
- independent uplink and downlink traffic
- *simulated transport protocol: UDP.*

[1]Capture environment. Platform: MS Windows XP. Capture software: Ethereal v. 0.10.14 (net driver: WinPcap v.3.1).

Table I
I-GAMING, MODELS.

Channel	Packet Size	Inter–arrival time
Uplink	Gamma($\alpha = 29.8$, $\beta = 1.5$)	Rayleigh ($\beta = 1.5$)
Downlink	Gamma($\alpha = 4.2$, $\beta = 29$)	Rayleigh ($\beta = 1.5$)

V. POLLING PROCEDURE

The scheduling schemes considered in this work require the PNC to periodically collect information on the DEVs traffic. To this end, we introduce a customized polling procedure that can be realized, in a completely standard–compliant way, by leveraging on the set of tools provided by the 802.15.3 specifications.

The polling procedure makes use of two customized control messages,[2] referred to as *commands*, which we have named `Stream Properties Command` and `Sender Status Command`.

The `Stream Properties Command` is used by a DEV to instantiate a new traffic flow with the PNC. The command contains the QoS parameters of the flow, such as Hard and Soft deadlines, which get registered by the PNC. Upon receiving a `Stream Properties Command`, the PNC assigns a unique identifier to the flow and allocates a reserved MCTA to the DEV, which will be used by the DEV to send periodic `Stream Status Commands` to the PNC. The command collects the *Stream Status Block* for all the active flows originating from the DEV. A *Stream Status Block*, in turn, is composed by the following fields:

- **Stream ID**. Stream identifier (8 bit).
- **Channel Time Request** ($CTRq$). Time required by the DEV to transmit the pending data (16 bit), resolution $1\mu s$, range $[0 \div 65535]\,\mu s$. The transmission of such data represents a *task*.
- **Waited Time**. Amount of time already consumed in queue by the current stream task (8 bit), resolution $1\,ms$, range $[0 \div 255]\,ms$).

The Stream ID field is that assigned to the data flow when it was instantiated, also reported in the Stream Properties Command. The $CTRq$ field is determined according to the amount of data the current task is composed of, the physical rate used by the DEV, and the ACK policy implemented by the DEV. The Waited Time field, finally, is updated by the DEV any time a new Stream Status Command is sent.

Subtracting the Waited Time fields from Hard (Soft) Deadline Value declared in the Stream Properties Command, the PNC determines the current value of the hard (soft) timeout for the considered task. The information delivered through these commands is used by the scheduling algorithm in the PNC to adjust the resource allocation in the successive superframe. In order for the scheduling algorithm to operate upon as much fresh info as possible, the MCTAs shall be allocated at the end of each superframe, as depicted in Fig. 1.

It might be worth remarking that the described procedure could be implemented in several different ways and the

[2]Customized commands can be realized by using the class of `Vendor Specific Command` encompassed by the standard.

solution here proposed does not claim in any way to be the best possible. Nonetheless, it takes the benefit of simplicity and adherence to the standard.

VI. Scheduling Algorithms

This section describes the scheduling algorithms considered in the study. Such algorithms originate from two distinct approaches: fair medium access and task deadline discrimination. The algorithms are executed by the PNC, on the basis of DEVs' streaming information gathered through the periodic polling cycle described in the previous section. More specifically, the streaming parameters that the scheduling algorithms work upon include:

- **Channel Time Request** ($CTRq$). Time required by the DEV to complete the current *task*.
- **Hard Timeout**. Time left before the task hard deadline is reached.
- **Soft Timeout**. Time left before the task soft deadline is reached.

The scheduling decisions are taken once per superframe, before the beacon broadcasting.

A. Generalized Processor Sharing (GPS)

Generalized Processor Sharing (GPS), together with its numerous variants [11], [12], is widely used in packet network scheduling and CPU processes management. GPS is intended to offer a fair service to every client, providing resources proportionally to the requests. To this aim, a GPS scheduler only needs to know the $CTRq$ for each DEV. More specifically, denoting by T the allocable time in a superframe and by $CTRq_i$ the time requested by the i–th stream, $i = 1, 2, \ldots, n$, then the time interval ideally assigned to the i–th stream is given by

$$\tau_i = T \frac{CTRq_i}{\sum_n CTRq_n} \ .$$

In practice, however, DEVs are not capable of using any arbitrary time allocation, since the transmission time of an elementary data unit is constrained by several factors, such as fragmentation and reassembly scheme, frame size, physical layer transmission rate, acknowledgment policy. Therefore, the scheduler will approximate the theoretical time share τ_i with the closest time interval that the DEV is capable of using.

B. Earliest Deadline First (EDF)

Earliest Deadline First (EDF) is one of the most known real–time algorithm with dynamic priority [13]. In a single–hop context (as in a 802.15.3 piconet) EDF represents an optimal scheduling policy: if a set of tasks is completely allocable under whichever discipline, then it is certainly allocable also under EDF[14]. More specifically EDF maximizes the service admission region for traffic classes with different deadlines.

The EDF scheduler requires that each stream specify the $CTRq$ and Hard Timeout parameters for its current task. The resource scheduling is, hence, performed in two steps. First, the EDF scheduler sorts the stream requests in ascending order of Hard Timeout threshold. Second, the scheduler assigns the requested $CTRq$ to each stream, starting from the first of the list (which has the closest timeout), till requests are all satisfied or resources run out.

The EDF approach is very effective from a real–time perspective and it is the progenitor of more advanced algorithms. In this work, beside basic EDF, we consider two evolutions, i.e., EDF with Discard (EDF–DS) and EDF with Soft/Hard deadlines (EDF–SH), which are described in the following.

C. Earliest Deadline First with Discard (EDF–DS)

In the basic version of EDF, the hard timeout threshold is only used to determine the priority of a task in the request service list: tasks that are closer to their timeout get served first. However, no check is made to verify whether the task service will be concluded within the timeout deadline. Hence, a task can be served after that its hard deadline has passed, thus resulting in a waste of resources. This drawback can be avoided by a preventive control on the task deadline: if a given task cannot be served within its timeout then the task is given no resources (EDF–discard).

EDF–DS enriches the original EDF scheduler by including this discard policy. In literature several discard policies, as well as medium access rearrangements, have been proposed and analyzed [13], [15]. In the context of HR–WPANs, however, simplicity is often preferable to a marginal performance gain that might be achieved by adopting more complex solutions. Hence, in this study we consider a simple EDF–DS strategy, in which a packet is discarded when its hard timeout cannot be met at the EDF–assign time.

D. Earliest Deadline First, Soft/Hard Deadlines (EDF–SH)

A further evolution of the basic EDF approach is the EDF–SH, which attempts to offer a privileged service to traffic characterized by both soft and hard deadlines, without severely affecting the other content. EDF–SH, in fact, attempts to serve the tasks before they meet their Soft Deadlines (admission in advance), provided that no other streams suffer job failures because of this.

The scheduler sorts the allocation requests in ascending order of *Soft Timeout*. Then, $CTRq$s are assigned starting from the first request of the list. If a violation occurs in the allocation of the i–th request, i.e., task i would not complete its service before its hard timeout, then the scheduler makes a backward search to verify which of the already allocated tasks can be delayed of $CTRq_i$ without violating their hard timeout constraint. If n of these streams can be deferred, then the i–th stream is anticipated of n positions in the service, in order to meet its deadline. Of course, in case the research fails, the usual discard policy takes place.

VII. Simulation Results

A. Settings

The performance analysis presented in the following has been carried out by using a WPAN simulator written in C++. The simulator includes FCSL, MAC and PHY layers, following the specifications contained in [5] for the 2.4 GHz band.

We fixed the superframe duration to $12\,ms$, which proved to be reasonable for a rather wide range of different traffic classes, on the basis of a preliminary study, here omitted for space constraints. The transmission rate of each DEV has been randomly selected in the set of admissible physical rates, i.e., $[11, 22, 33, 44, 55]$ Mbps, with probability $[0, 0.1, 0.2, 0.3, 0.4]$, respectively, which yields an average rate of 44 Mbps. The Frame Error Rate (FER) has been set to 4% for a reference frame payload length of 2044 bytes. Each simulation lasted for 20 (virtual) minutes, starting from the time all the DEVs were connected to the PNC.

B. Results

In this section, we present and discuss the performance achieved by the scheduling algorithms in mixed traffic scenarios. As in [7] and [8], performance is measured in terms of *job failure rate* (JFR), i.e., fraction of apckets that are not completely or correctly delivered within the associated hard deadline. We say that the piconet offers *high QoS* when each stream experiments a JFR less than 1%, on the average. Notice that, for clarity, we do not plot the EDF–SH curves when the simulated scenario does not include any soft–QoS applications, since its behavior in this case is the same of the EDF–DS algorithm.

We have performed two distinct simulations series. In the first simulation campaign, we have considered a limited set of scenarios, each with a different mix of the three traffic types. To challenge the scheduling algorithm, we have imposed a high traffic load. Fig. 2 summarizes the results obtained for the five scenarios considered. The upper graph in the figure shows the *per–traffic class* JFR, obtained by using GPS, EDF and EDF–DS scheduling algorithms[3] for the specific traffic mix represented in the immediately underneath graph. Notice that, in the right–most traffic mix (20 VoIP full–duplex streams plus 20 i–gaming peers), we limited to 40% the amount of allocable resources in order to produce some appreciable results in a reasonable simulation time.

At a first glance, we observe that GPS performance, which was comparable with EDFs in homogeneous traffic scenarios, now shows a remarkable decay, with JFR also $8 \div 16$ times higher than that obtained with EDF algorithms. This is expected since GPS does not take into consideration the residual lifetime of data packets, but only the $CTRq$ declared by the sources. Therefore, GPS privileges sources with low bandwidth demand, such as VoIP, to those having more stringent delay requirements.

In heterogeneous scenarios, in fact, the awareness of tasks deadline plays an essential role. Hence, scheduling algorithms that make use of this information, such as EDFs, are able to maintain the service in a high QoS region even where other policies yield practically unacceptable performance.

In the second set of simulations, we have compared the different scheduling algorithms for increasing traffic load. More

[3]EDF–SH results have been omitted since they basically overlap with EDF–DS ones.

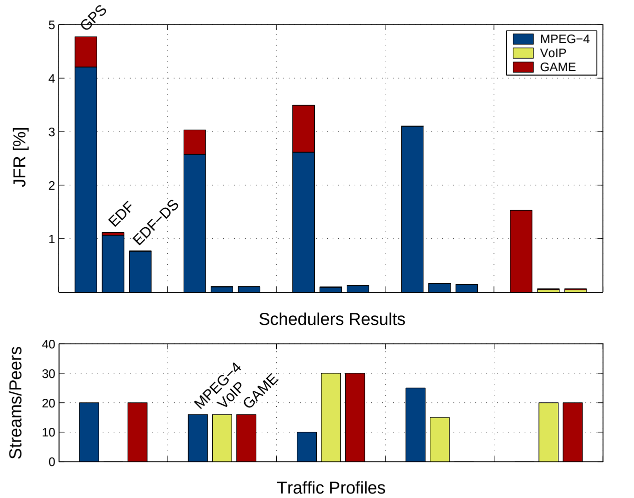

Figure 2. Cumulative JFRs (a) for GPS, EDF and EDF–DS in different traffic scenarios (b). (FER=4%)

specifically, the piconet was initially interested by 16 voice and 16 i–gaming sessions, corresponding to a modest traffic load (approx 20% of channel occupancy). Hence, MPEG–4 streams were progressively introduced. Fig. 3 depicts the JFR vs the number of active MPEG–4 flows for GPS, EDF–DS and EDF–SH. (For clarity, we omit pure–EDF results, which are in good agreement with what already observed in the previous cases.)

The results confirm the previous consideration on GPS and EDF–DS performance, as well as the substantial equivalence between EDF–DS and EDF–SH algorithms, though EDF–SH undergoes a very marginal penalization in the joined MPEG–4/VoIP traffic, balanced by an extremely high QoS for i–gaming. Notice, that this fact is observed in a traffic region where MPEG–4 streams are experiencing low quality levels, so that the scenario is unlikely to hold in practical cases. The EDF approach generally exhibits a threshold–behavior: the offered service is excellent until the traffic load approaches a critical level, after which performance undergoes rapid deterioration.

Fig. 4 shows the mean delay values measured in the same test conditions. Notice that the delay is obtained only for the packets that are successfully delivered to the destination, so that the results shown in Fig. 4 are significative only in the region where the JFR is acceptable. We observe that GPS inevitably undergoes a generalized progression in the performance decay, whereas EDFs schemes are able to offer a sort of isolation between different classes.

It is also interesting to notice that, in low or moderate load conditions, EDF–SH does not provide any appreciable latency gain on EDF–DS, in spite of its more complex scheduling mechanism. Results become more favorable to EDF–SH for high traffic loads, a condition that, however, is unlikely to hold in practical cases.

VIII. Conclusions

In this work we have compared some possible scheduling algorithms for providing high QoS to multimedia traffic in 802.15.3 piconets. To this end, we have proposed a simple

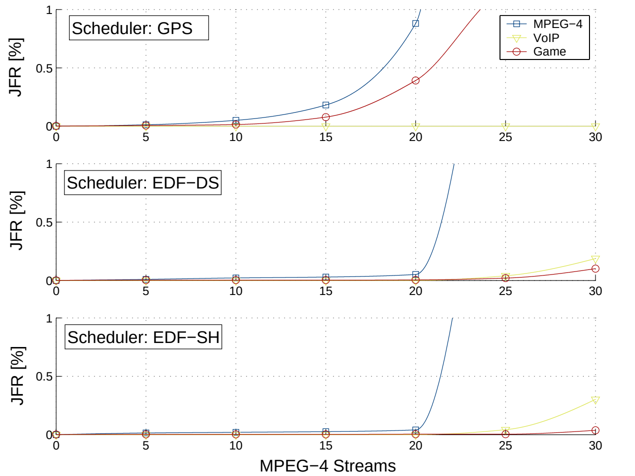

Figure 3. JFRs *per traffic class* measured in a moderately loaded piconet, while increasing the number of MPEG–4 transmissions. GPS, EDF and EDF–DS schedulers.

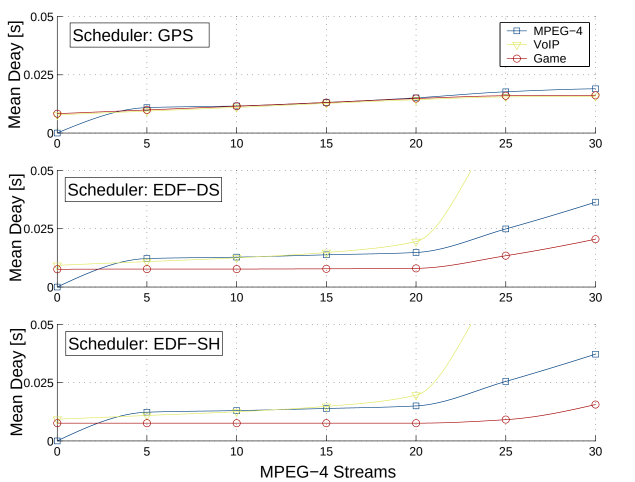

Figure 4. Delays *per traffic class* measured in a moderately loaded piconet while increasing the number of MPEG–4 transmissions. GPS and EDF–DS schedulers.

and standard–compliant polling mechanism for the piconet coordinator (PNC) to gather traffic information from the DEVs. Hence, we have performed several simulations in different conditions, to explore pros and cons of the considered scheduling algorithms.

The analysis has privileged applicative scenarios, in which all the algorithms have proved to be able to provide high QoS service to different type of applications.

In general, EDF–based algorithms have shown better performance than GPS. Furthermore, EDF–DS and EDF–SH have shown some performance gain on pure EDF, whereas the higher complexity of the EDF–SH mechanism has not proved to pay enough in terms of performance improvement with respect to EDF–DS, so that the last algorithm seems to be preferable in almost all the cases.

In conclusion, EDF–based schedulers are able to provide high QoS in presence of heterogeneous multimedia traffic flows. To reach this goal, however, EDF algorithms need to get access to some cross–layer information, such as the hard and soft timeout, which depend on the application. Therefore, a significative performance gain might be expected from an optimization of the polling and signalling procedures that realize the cross layer interaction.

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