INTERNATIONAL JOURNAL OF SATELLITE COMMUNICATIONS AND NETWORKING
Int. J. Satell. Commun. Network. 2004; **22**:503–532 (DOI: 10.1002/sat.797)

Packet scheduling for the delivery of multicast and broadcast services over S-UMTS

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SUMMARY

We investigate the packet-scheduling function within the access scheme of a unidirectional satellite system providing point-to-multipoint services to mobile users. The satellite system may be regarded as an overlay multicast/broadcast layer complementing the point-to-point third generation (3G) mobile terrestrial networks. The satellite access scheme features maximum commonalties with the frequency division duplex (FDD) air interface of the terrestrial universal mobile telecommunications system (T-UMTS), also known as wideband code division multiple access (WCDMA), thus enabling close integration with the terrestrial 3G mobile networks and cost-efficient handset implementations. We draw our attention on one of the radio resource management entities relevant to this interface: the packet scheduler. The lack of channel-state information and the point-to-multipoint service offering differentiate the packet scheduler in the satellite radio interface from its counterpart in point-to-point terrestrial mobile networks. We formulate the scheduler tasks and describe adaptations of two well-known scheduling disciplines, the multilevel priority queuing and weighted fair queuing schemes, as candidates for the time-scheduling function. Simulation results confirm the significance of the transport format combination set (TFCS) with respect to both the resource utilization achieved by the scheduler and the performance obtained by the flows at packet-level. The performance gap of the two schemes regarding the fairness provided to competing flows can be narrowed via appropriate selection of the TFCS, whereas the achieved delay and delay variation scores are ultimately dependent on the packet-level dynamics of individual flows. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: satellite UMTS; WCDMA; MBMS; streaming; packet scheduling; radio resource management

1. INTRODUCTION

The delivery of multimedia broadcast and multicast services to mobile users via satellite has been amongst the main areas of current mobile satellite communications' industry activities. The inherent broadcast capabilities of satellites make them an attractive platform for the delivery of these services, in particular those featuring large and widely distributed audience. On

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the other hand, the limited success of the stand-alone satellite system model in capturing the consumer market, via provision of the same set of services with the terrestrial mobile network, has motivated the re-consideration of the satellite role in service provision [1]. In this context, the integration of the satellite universal mobile telecommunications system (S-UMTS) component with the third generation (3G) terrestrial mobile networks is regarded as a key factor for the success of the system.

The provision of point-to-multipoint services over the 3G terrestrial mobile cellular networks is investigated within the third generation partnership project (3GPP) multimedia multicast/broadcast services (MBMS) framework [2]. MBMS data are mapped onto appropriate radio network bearers and are transmitted over the air in parallel to unicast data. The detailed radio network procedures for the support of MBMS services are currently under standardization [3].

The possible role of satellites in the delivery of point-to-multipoint services to mobile users is further advocated by the three operational digital radio satellite broadcasting systems, namely WorldSpace, Sirius and XM Radio, and the—planned for 2004—launch of mobile broadcasting services in Japan and Korea [4]. In Europe, much research effort has been devoted to the satellite digital multimedia broadcasting (SDMB) system concept [5], which targets close integration with the terrestrial mobile networks so that it can penetrate the mass consumer market via cost-effective handheld terminals. The SDMB concept features in a series of European research projects, funded both by European Union (EU) and European Space Agency (ESA). With respect to the satellite radio interface aspects, in particular, the use of the UMTS terrestrial radio access (UTRA) frequency division duplex (FDD) mode, better known as wideband code division multiple access (WCDMA) [6], has been explored in the EU SATIN project[‡] and is currently revisited in the context of the EU MAESTRO[§] project.

This paper focuses on one of the radio resource management (RRM) entities of the system, the packet scheduler. Firstly, we briefly review the radio interface engineered within the SATIN and MAESTRO projects and the proposed RRM strategy addressing its constraints. We then proceed in Section 3 with the description of the packet scheduler role, insisting mainly on the functional differences from its counterpart in T-UMTS. The formulation of the problem in mathematical notation is given, before the two scheduling disciplines, and adaptations of well-known schemes with broad use in wired networks, are presented. The two schemes are evaluated via simulations in Section 5, following the methodology described earlier in Section 4. Simulations address their ability to satisfy the packet-level QoS requirements of individual flows under worst-case (high-load) scenarios and preserve the system transmit power. We summarize our findings and conclude the paper in Section 6.

2. SYSTEM ARCHITECTURE, RADIO INTERFACE AND RRM STRATEGY

2.1. System architecture

The system architecture is outlined in Figure 1. The baseline SDMB system is unidirectional [5]; there is no return link via the satellite. A return link via T-UMTS is available to the users with

[‡] The project SATIN (Satellite UMTS IP-based network) was partly funded by the European Commission under the 5th research framework programme, http://www.ist-satin.org.

[§] The integrated project MAESTRO (Mobile applications and services based on satellite and terrestrial interworking) is partly funded by the European Commission under the 6th research framework program, http://www.ist-maestro.dyndns.org.

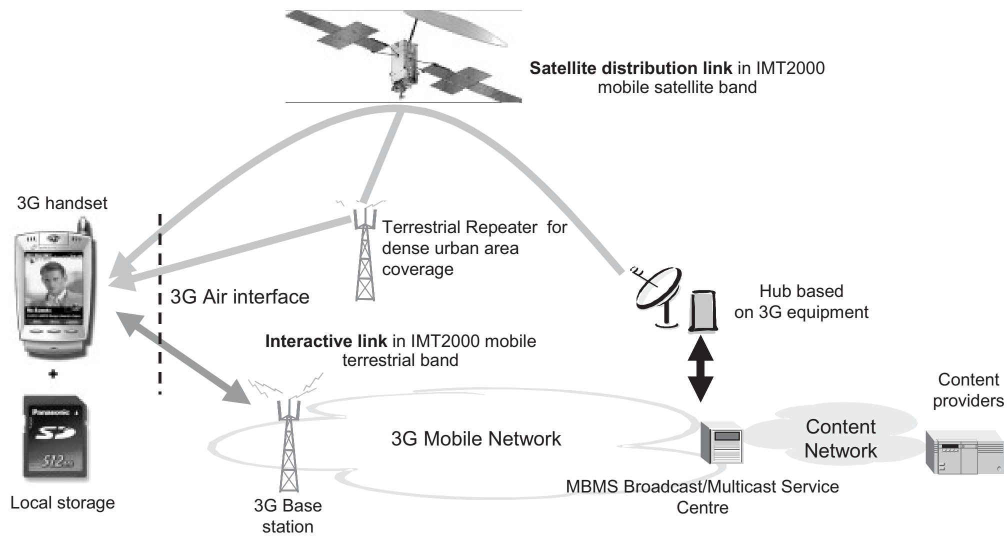

Figure 1. SDMB system and position with respect to the terrestrial 3G mobile networks.

dual-mode handheld terminals, but it may only be used for specific functions via the terrestrial radio access network, such as access to content decoding keys and retrieval of multimedia content blocks corrupted on the satellite forward link, rather than real-time interaction between the user and the satellite radio access network (S-RAN). The S-RAN is physically located within the satellite gateway node (Hub) and interfaces with the core network (CN) of the terrestrial mobile network and the 3GPP broadcast multicast-service center (BM-SC) [2]. Connections over the satellite radio interface, packet data protocol (PDP) messaging [7, Chapter 5] and feedback/loop mechanisms, such as power control and automatic repeat request (ARQ) protocols, between the user equipments (UEs) and the S-RAN are not feasible. The configuration of UE lower layers may only be based on unidirectional signalling from S-RAN to UEs without acknowledgments from the latter. A significant feature of the SDMB system architecture is the introduction of terrestrial repeaters. The repeaters are physically co-located with T-UMTS Node Bs, retransmit the satellite signal and ensure coverage in-door and in built-up areas [8]. The handheld terminal, enhanced with minimum additional functionality for reception of the SDMB signal, combines the direct satellite signal with the replicas produced by the repeaters. Note that the number of signal components is larger and the delay spread is wider than in T-UMTS, therefore the SDMB terminal RAKE receivers need more fingers in order to benefit from diversity [9].

Overall, the system can be envisaged as a Content Delivery Network, primarily oriented towards *streaming* (e.g. audio/video broadcasting, alert and emergency announcements) and download applications (e.g. infotainment, entertainment, software delivery). Notably, the classification of applications under the two service delivery modes, i.e. streaming and download (push and store), is not strict. In fact, all non-real time services may be provided in both modes. The mechanism for the service delivery to a particular group is determined by other factors including terminal capabilities, policies, timing context of service. With streaming services the multimedia content is played directly upon reception at the user terminal, whereas with download services the multimedia content is stored locally in a cache for later processing (pre-stored content).

2.2. Radio interface and channel mapping

In general, the WCDMA layer 2 is functionally split into four sub-layers namely the radio link control (RLC), the medium access control (MAC), the packet data convergence protocol (PDCP) and the broadcast/multicast control (BMC) sub-layers. The first two sub-layers exist on both the data and control planes, whereas the last two exist only in the data plane. The data transfer services offered by MAC to RLC and those provided by the physical layer to MAC vary and are grouped into sets of functions abstracted into the terms *logical channel* and *transport channel*, respectively [10]. The overall service provided by layer 2 is referred to as radio bearer (RB). Control-plane signalling between UEs and the terrestrial RAN is handled by the radio resource control (RRC) sub-layer, which is part of the UTRA layer 3.

Only *common* WCDMA channels, which address groups of users rather than individual users, are relevant to the satellite radio interface. Moreover, given that the system is unidirectional, only downlink WCDMA channels are applicable. Figure 2 shows the downlink common WCDMA channels envisaged for the MBMS data transfer according to the air interface proposed in Reference [9]. Multicast/broadcast service flows are mapped one-to-one on common traffic channels (CTCHs) at RLC sub-layer and forward access channels (FACHs) on the MAC sub-layer, which may then be multiplexed at physical layer on secondary common control physical channels (S-CCPCHs). The latter feature fixed spreading factors (SFs), which can vary over the whole range defined in 3GPP standards [11], i.e. from 4 to 256, and no power control. A separate S-CCPCH of low rate, called 'master S-CCPCH' is reserved for signalling related to service notification. The interested reader will find more details on the proposed air interface in Reference [9].

Note that recent standardization work progress in the 3GPP MBMS framework has led to the definition of new logical channels, which are exclusively devoted to the support of MBMS over the terrestrial RAN. The MBMS traffic channel (MTCH) carries MBMS data, whereas MBMS signalling is carried over the MBMS control channel (MCCH) [3]. With respect to packet

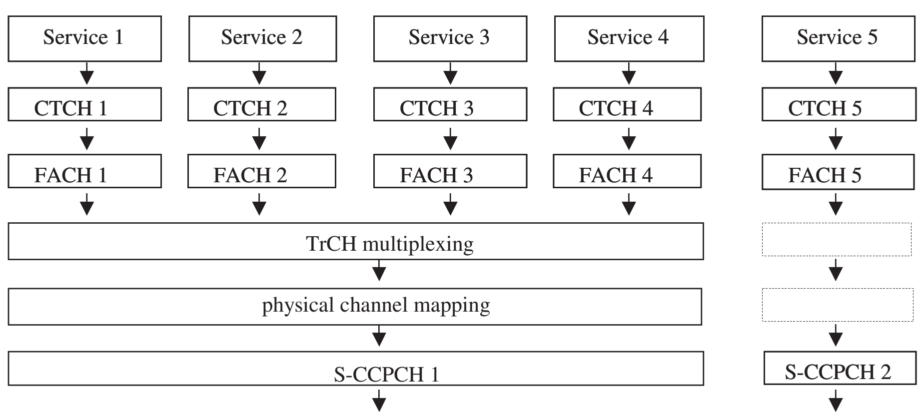

Figure 2. The common downlink WCDMA channels used for MBMS data transfer over the satellite radio interface.

scheduling, there is no difference between CTCH and MTCH. In the following, we maintain the assumptions and notations of the access scheme in Reference [9], e.g. CTCH instead of MTCH, pointing out that the following study is fully applicable in the context of the new channels defined by 3GPP.

2.3. Radio resource management requirements and constraints

From radio resource management (RRM) point of view, the lack of real-time interaction between the user and the S-RAN renders downlink power control irrelevant. Anyway, the closed-loop power control mechanism is less effective on satellite links [12] and is not available for the FACH transport channel. More generally, this lack of interaction implies that the S-RAN has to do without the assistance of user-side measurements regarding the quality of the downlink; this information is exploited in the two-way unicast T-UMTS by the short-term radio resource management functions (e.g. packet scheduling) to optimize the network resource allocation [6, Chapter 10]. Even in the presence of a satellite return link, the use of dedicated channels for the communication of radio link measurements back to the S-RAN would be in contradiction with the attempts to save radio resources in the data transfer plane. In summary, the unidirectional system nature and its point-to-multipoint service offering impose both hard and soft limitations, respectively, regarding the channel-state information that becomes available to the S-RAN.

The main RRM functions relevant to the satellite radio interface are the admission control (AC), load control (LC), packet scheduling (PS) and the radio bearer allocation and mapping (RBAM) function [9]. Download services are mainly handled by the broadcast scheduler (BS). The RBAM module is responsible for the radio bearer (RB) configuration, i.e. the estimation of the required number of transport/physical channels and their mapping together with the actual transport format combination set (TFCS) for each physical channel. This block lies functionally within RRC and is in close-cooperation with the other RRM functional entities.

Two RRM operational modes are possible, each one implying different functionality for some of the aforementioned RRM blocks [13]: in *mode A* the RBAM dimensions the system for some interval of time, over which the traffic mix remains the same (for example, in the order of 1 h). Over this interval, called subsequently *reconfiguration* interval, the channel mapping and the RB configuration remain fixed. The AC function has to consider the availability of FACHs as this arises from the fixed RB configuration, when deciding on the admission of a new service. In *mode B* it is the AC that derives the RB mapping in an *ad hoc* manner, i.e. without any prior configuration [14].

In both modes, the packet scheduler will have to cope with a number of S-CCPCHs, whereupon a set of CTCH/FACHs is mapped. In mode A, the mappings are drawn once per reconfiguration interval from the RBAM function and what changes over time is the status of the individual pre-configured FACHs, which may be active or idle when a service flow is carried over them or not, respectively. In mode B, what changes over time is the actual channel mapping. At each time instant, the S-CCPCH configuration features only active channels. In both modes, there are two possibilities for mapping services, namely logical/transport channels, onto physical channels: in the standard *bin-packing*-based method, the aim is to fully utilize as few as possible physical channels. In the *power-aware packing*-based method, services with similar E_b/N_0 requirements are mapped on the same physical channel, in an attempt to make a more efficient use of power resources. We describe in more detail the two channel mapping methods in Appendix A.

3. PACKET SCHEDULING

The role of the scheduler in the proposed radio interface is apparently different than in the standard UTRAN. There the packet scheduler allocates the radio resource in short-term having as a significant criterion for its allocations the state of the individual links (channel state). In the proposed satellite access scheme, information regarding channel state is not available at the scheduler. In any case, even if such information were available, it would have to be exploited in a manner accounting for the point-to-multipoint nature of services: decisions about the scheduling of a single service data flow should consider the state of several links corresponding to the users of each group.

Therefore the role of the packet scheduler is not that dominant in determining the system throughput as it might prove to be in the terrestrial UMTS [6, Chapter 10]. Nevertheless, the scheduler is still responsible for two important tasks that are executed with a period equal to the time transmission interval (TTI) of the radio bearers.

- Time-multiplexing of flows with different QoS requirements into fixed SF physical channels, in a way that can satisfy these requirements. The higher priority streaming services feature delay jitter and rate requirements: the higher the delay jitter values the larger the playout buffer at the mobile terminal has to be. On the contrary, download services are organized into data carousels—for example, see Reference [15]—that only require the provision of a constant, in long-term, mean rate that will preserve the target average download time.
- Adjusting the transmit power for the data flows. Criteria for the power allocation may be the packet/transport block size to be served or knowledge of the expected audience distribution within the beam. Hence, this power adjustment does not feature the granularity of the conventional fast power control mechanism and is limited to a small set of values.

3.1. Time scheduling function formulation

The scheduler treats independently each physical channel (S-CCPCH) every TTI. For each physical channel, the scheduler is provided with a separate TFCS. The size of the TFCS, namely the number of transport format combinations (TFCs) it comprises, differs from S-CCPCH to S-CCPCH and is a function of the dynamics of the service data flows mapped on a given S-CCPCH.

Each TFC, in turn, consists of transport block sets (TBSs) corresponding to the logical/transport channels mapped on the same S-CCPCH (Figure 3). The selection of a TFC by the scheduler in a given TTI directly determines the per CTCH/FACH TBS size, namely how much data from that channel will be forwarded to the physical layer in the respective TTI. The set of the different TBSs corresponding to one CTCH/FACH forms its transport format set (TFS), with each TBS being part of a single transport format (TF). The exact number of physical channels at a specific time instance and the corresponding mapping of transport channels onto the code channels are defined by the RBAM and/or AC, depending on the RRM operational mode (see Section 2.3).

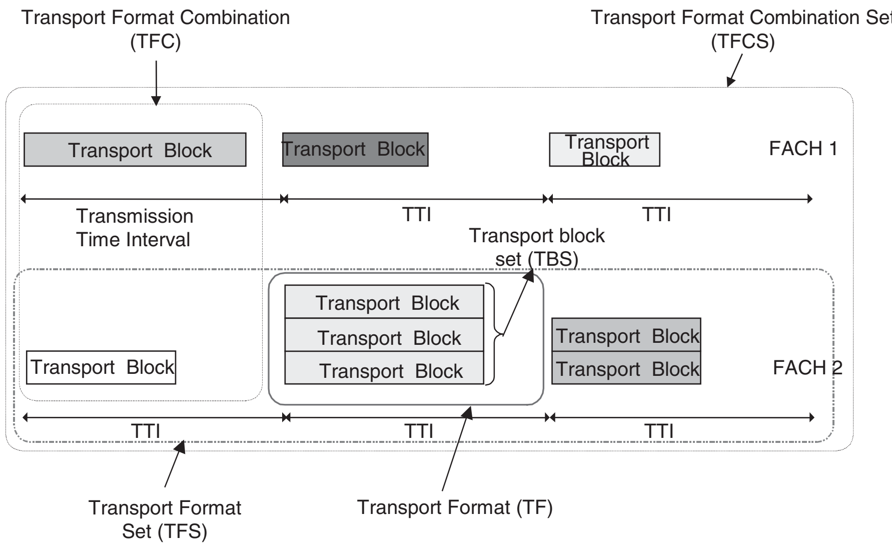

Figure 3. Example of data exchange between MAC and the physical layer when two FACHs are multiplexed.

Let TBS $size_{ij}(k)$ denote the size of the kth TBS of the jth FACH, $1 \leqslant j \leqslant N(i)$, mapped on the ith S-CCPCH, $1 \leqslant i \leqslant M$. $N(i)$ is the number of FACHs mapped on the ith S-CCPCH, while K_{ij} is the TFS size of the jth FACH mapped on the ith S-CCPCH. We assume that the TBS sizes corresponding to the TFs of each FACH are sorted in increasing order, namely

$$\text{TBS } size_{ij}(k) \leqslant \text{TBS } size_{ij}(k+1), \quad 1 \leqslant k < K_{ij} \tag{1}$$

Each TFC corresponds to a certain amount of data R_l passed from the scheduler to the Layer 1, upper-limited by the maximum allowed data rate of the physical channel. The scheduler is given L TFCs per S-CCPCH, obeying the limitations of 3GPP standards, for example, there is an upper limit to the TFCS size L that depends on the terminal class capabilities [6, Chapter 6]. The task of the scheduler is to select every TTI and for each S-CCPCH i some 'appropriate' TFC l, $1 \leqslant l \leqslant L$, featuring a certain TBS size, $\text{TBS}(l,m)$ $1 \leqslant m \leqslant N(i)$, for each one of the $N(i)$ FACH channels multiplexed on it. The actual context of the term 'appropriate' is dictated by several factors, like the service QoS requirements and the physical channel utilization efficiency, and differentiates the one scheduler from the other. This differentiation is summarized in the term scheduling discipline, i.e. in the way the semi-statically fixed capacity of S-CCPCHs is time-shared among the different FACHs.

In the following, two of the possible disciplines are analysed further. Both of them are adaptations of well-known scheduling disciplines that have been used for years in the context of wired networks.

3.2. *Multi-level priority queuing (MLPQ)-based scheme*

This is effectively the adaptation of the multi-level, non-preemptive priority discipline (for example, see Reference [16]) to the WCDMA context. In our case a CTCH queue at the RLC level may carry one service/flow or a broadcast schedule carrying multiple services (content types). The original scheme favours by default the high priority classes, being able to assure minimum delay for their packets, while it provides no guarantees for lower priority classes.

The $N(i)$ FACHs mapped to a single code channel i are ordered from 1 to $N(i)$, according to their priority. The usual convention is followed, i.e. a lower order number implies a higher priority. The choice of the proper TFC for a given TTI includes some search over the possible TFCs included within the TFCS of the code channel.

The scheduler first seeks to allocate the maximum TBS size to the first FACH. If the queued data q_1^i are more than the maximum supported TBS size for this FACH in the TFCS, the selected TBS size TBS $\text{size}(i,1)^*$ will be the maximum one available in the TFCS. Otherwise, the selected TBS size is the minimum available in the TFCS that can serve the queued data, padding being applied when the match between queued data and TBS size is not exact:

$$\begin{aligned} &\text{if } q_1^i > \text{TBS size}_{i1}(K_{i1}) \ \text{TBS size}(i,1)^* = \text{TBS size}_{i1}(K_{i1}) \\ &\text{else}: \ \text{TBS size}(i,1)^* = \text{TBS size}_{i1}(n') \\ &\text{with}: n' = \min_z \{z: \ \text{TBS size}_{i1}(z) \geqslant q_1^i\} \end{aligned} \tag{2}$$

Out of the whole TFCS, a reduced TFCS, TFCS_R^1, is derived for each physical channel

$$\text{TFCS}_R^1 = \left\{ \bigcup_{l \in TFCS} \text{TFC}_l : \text{TBS}(l,1) = \text{TBS size}(i,1)^* \right\} \tag{3}$$

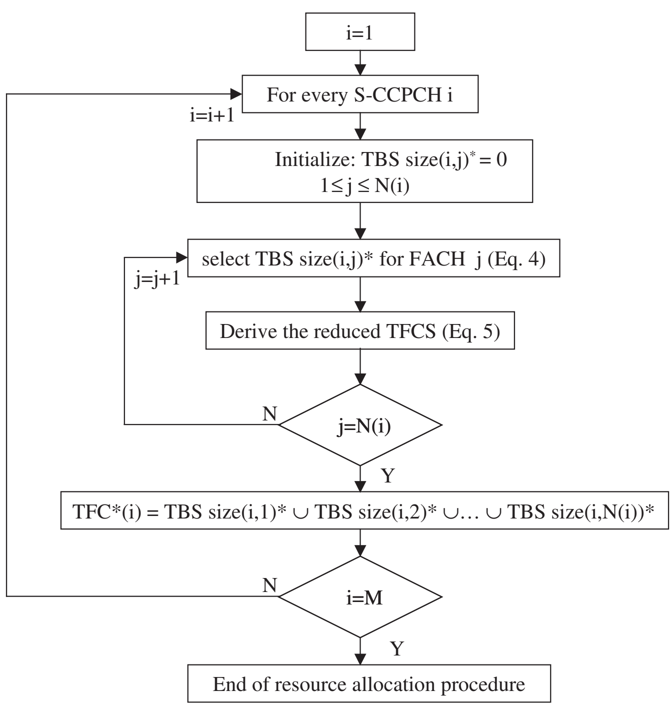

Figure 4. Outline of the WCDMA-adapted version of MPQ-based discipline.

The procedure is repeated recursively for each one of the $N(i) - 1$ remaining FACHs, namely for each FACH j

$$\begin{aligned} &\text{if } q_j^i > \text{TBS size}_{ij}(K_{ij}) \ \text{TBS size}(i,j)^* = \text{TBS size}_{ij}(K_{ij}) \\ &\text{else}: \ \text{TBS size}(i,j)^* = \text{TBS size}_{ij}(n') \\ &\text{with}: n' = \min_z \{z: \ \text{TBS size}_{ij}(z) \geqslant q_j^i\} \end{aligned} \tag{4}$$

where the search is now over the reduced TFCS that came out of the previous step

$$\text{TFCS}_R^j = \left\{ \bigcup_{l \in \text{TFCS}_R^{j-1}} \text{TFC}_l: \ \text{TBS}(l,j) = \text{TBS size}(i,j)^* \right\} \tag{5}$$

When more than one CTCHs, of the same priority, is multiplexed on a single S-CCPCH, the channels may be served in round-robin mode. The MLPQ-based scheduling algorithm is outlined in Figure 4.

3.3. Weighted fair queuing (WFQ)-based scheduling

This scheme was motivated by the well-known features of WFQ [17]: capability to guarantee a minimum bandwidth per bearer/flux or per set of bearers grouped together for traffic handling purposes, feasibility of upper-bounded queuing delays, fairness in bandwidth-sharing among flows in accordance with the weights assigned to them.

The proposed WFQ scheduler is more specifically based on the *Virtual Spacing* policy that uses the concept of *Virtual Time* [18]. The virtual spacing policy is applied simultaneously to each one of the code channels multiplexing logical/transport channels and involves the following parameters:

- r_i—*spacing rate or 'weight' associated with CTCH i*: $T_i = 1/r_i$ corresponds to the share of the physical channel capacity allocated to the RLC queue.
- TSTP_i—*time stamp associated with CTCH i*: tags the packets at their arrival and is used to order their scheduling.
- *TV—virtual spacing time of the system*: the time stamp of the last packet sent out of the queues, namely of the last packet served or being served.

The weights are primarily set according to the rates of the multiplexed service flows. The weight distribution amongst flows can be adapted whenever necessary, e.g. as a response to a new service admission or change of channel mapping configuration.

From an implementation point of view, the main packet memory is complemented by two more structures: the *scheduler* and a *global linked list* (LLr). The scheduler orders the incoming packets according to their computed time stamps, storing in a single list the addresses of packets with the same, or approximately the same, time stamp, with a precision that depends on the implementation. The LLr carries the addresses of the packets to be eventually forwarded to the physical layer. The entries to the LLr are made according to the scheduler emission process, described in 3.3.2. Although the packet serving order within a given CTCH/FACH is first come first served (FCFS), the serving order of packets from different logical channels takes place in increasing time stamp order and is implemented by the combination of the scheduler and the LLr. More specifically the virtual spacing scheduling algorithm consists of the following three processes:

3.3.1. Reception process. When a packet arrives at the queue of CTCH i, it is stored in the packet memory. The time stamp TSTP_i corresponding to this packet is computed—$\mathrm{TSTP}_i = \max(\mathrm{TV}, \ \mathrm{TSTP}_i + \mathrm{T}_i)$—and the address of the packet is written in the corresponding line of the scheduler. If no other packet address is written in the corresponding line by that time, the occupancy bit is set to one. If there are more packet addresses in the same line, then the new address is added to the linked list of addresses (Figure 5).

3.3.2. Scheduler emission process. The scheduler emission process is executed at each TTI. First the LLr is scanned: if it is empty (or about to become empty), then the scheduler is scanned (Figure 6). The linked list of packet addresses in the line of the scheduler with the smallest time stamp is added to the LLr. After emission from the scheduler the occupancy bits are reset accordingly and the virtual spacing time of the system (TV) is set to the Time Stamp of the scheduler line that has been delivered ($\mathrm{TV} = \mathrm{TSTP}_{\mathrm{new}} = \mathrm{TSTP}_{\mathrm{lowest}}$)—(Figure 7).

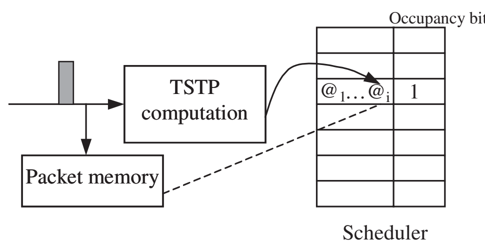

Figure 5. Virtual spacing: arrival of a packet.

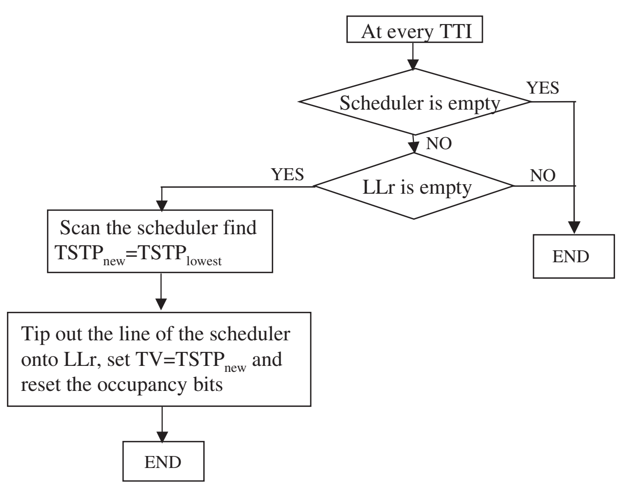

Figure 6. Scheduler emission process (algorithm).

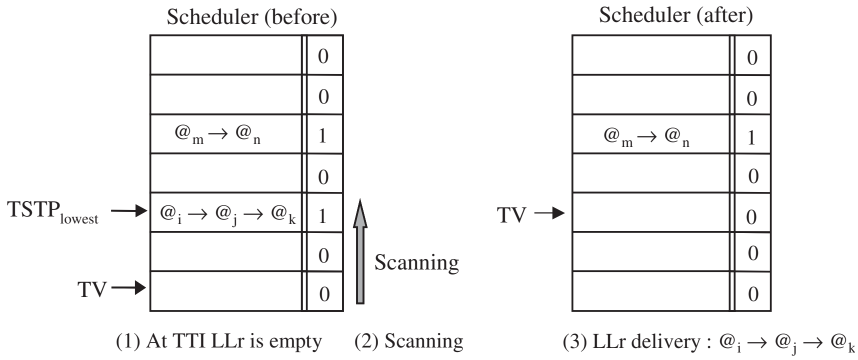

Figure 7. Scheduler emission process (description).

The scanning of the scheduler or, as it is called, the time stamp sorting problem (see Reference [18] for details) is the heart of the implementation issues with regard to WFQ policies in general, as the processing time constraint cannot be ignored for transmission rates in the order of Mb/s. In our context, the problem is less dramatic due to the lower rates considered (<384 kbps per code channel).

3.3.3. Re-emission process. The re-emission process refers to the extraction of packets from the packet memory according to the addresses stored at the LLr and the selected TFC in the respective TTI and their forwarding to the lower layer.

The execution of these processes has to be done in such a way that no service slot (TTI) be ever lost due to any lack of synchronization between the processes. The execution of the scheduler emission process every TTI serves this purpose.

4. SIMULATION SET-UP AND METHODOLOGY

The simulations with the scheduler focus mainly on the efficiency of the time-multiplexing function. The simulations address the worst-case scenarios for each S-CCPCH, i.e. the intervals over which all FACHs mapped to a physical channel are active. This is the least favourable scenario from the services point of view, namely regarding the potential of the packet scheduler to guarantee the rate and the jitter requirements of the service data flows. In other words, these cases can be regarded as a lower bound on the scheduler performance, as perceived by the flows, and correspond to maximum buffer requirements at the terminal side, in order to absorb the jitter generated at the RLC queues.

4.1. Service types

The service types considered for the simulations are given in Table I. Service types under the streaming category correspond to separate flows, mapped one-to-one to logical channels (CTCHs). Download services are grouped into data carousels and are treated with lower

Table I. Services considered for simulations and their QoS characterization (class, traffic handling priority).

Service category	UMTS QOS class	Service type	Guaranteed rate (kbps)	Traffic handling priority
Streaming services	Streaming	Audio streaming	32/64	1
	Streaming	Video streaming	64/128/256	1
	Interactive*	Location-based services	16	2
Download services	Background	Webcasting	N/A	Normal
		Rich audio/video info		High
		Pre-stored movie on demand		Low
		Pre-stored video clips on demand		Low
		Pre-stored radio on demand		Low
		Pre-stored music on demand		Low
		Software download		Normal

*The use of the word interactive in this table deviates a little from the original context of the word interactive within 3GPP. LCS are provided via the streaming service delivery mechanism, i.e. they are not cached. However they do not impose the strict per-packet requirements of audio/video streaming but rather a requirement for the total delivery time of the content.

priority. There is no guaranteed rate attribute for individual services but some mean rate should be maintained for the whole carousel that is mapped on a single CTCH/FACH.

4.2. Traffic modelling

Regarding traffic modelling, the main problem we had to face was the lack of models for streaming applications. Few studies are available in the literature mainly because of the proprietary protocols used for such applications and the limited insight to their code. To our knowledge, only one model has been proposed for streaming audio, the structural RealAudio model in Reference [19]. For our simulations, the exponential ON–OFF model with high activity factor (0.8) was retained as the reference model for audio streaming. Additional simulations have been performed with the RealAudio model in order to show the impact of packet-level dynamics, namely different short-term burstiness characteristics, on the obtained delay and delay jitter values. For video streaming services we made use of publicly available trace files [20]. The models are summarized in Table II.

4.3. Channel mapping

The derivation of the required number of logical channels and the respective mappings are the outcome of an elaborate procedure that has the user profiles as starting point. On the basis of these profiles, estimations about the number of the system subscribers and their evolution as well as assumptions about the audience (popularity) of individual services, which account for the point-to-multipoint nature of the services, the traffic load at the system level¶ may be computed (see appendix in Reference [9]). The system load is then input to the RBAM module that derives the required number of FACHs and their mapping on physical channels. In the

¶The system level in this case is a single satellite beam. However, extension to different scales is straightforward.

Table II. Traffic simulation models.

Service	Traffic models	Packet size (bytes)	Model parameters/info
Audio streaming	Exponential ON–OFF RealAudio structural model [19]	500	Activity factor = 0.8 Mean off duration = 100 ms Idle intervals: multiple of 1.1 s
Video Streaming	Video trace	500	H.263 files at 64/128/256 kbps target bit rate
LCS	CBR	120	—

Table III. Channel mapping derived via the power-aware packing method.

S-CCPCH	1–2	3	4	5	6	7–8
Spreading factor	16	16	16	8	8	8
Streaming FACHs (kbps)	1 × 32 4 × 16	1 × 64 2 × 32	2 × 64	1 × 128 2 × 64	2 × 128	1 × 256
Streaming FACH sum (kbps)	96	128	128	256	256	256
Download FACHs (kbps)	1 × 48	1 × 20	1 × 20	1 × 48	1 × 48	1 × 52

Table IV. Channel mapping derived via the bin-packing method.

S-CCPCH	1	2	3	4	5	6
Spreading factor	8	8	8	8	8	8
Streaming FACHs (kbps)	1 × 256 1 × 32 1 × 16	1 × 256 1 × 32 1 × 16	2 × 128 1 × 32 1 × 16	1 × 128 2 × 64 1 × 16	2 × 64 2 × 16	1 × 64 1 × 32 2 × 16
Streaming FACH sum (kbps)	304	304	304	272	160	128
Download FACHs (kbps)	—	—	—	1 × 32	1 × 144	1 × 176

following, we consider the mappings that were computed with the power-aware packing method (Table III) and the bin-packing method (Table IV) for the traffic mix in Appendix B. The power-aware packing method, having as inputs the E_b/N_0 requirements of individual service types, relied on the link-layer characterization of the combined channel, due to the co-existence of satellite and terrestrial repeaters, in Reference [21].

A major task related to the scheduler configuration is the derivation of the TFCS. Unfortunately, no strict rules apply there so that the task becomes a trial-and-error exercise. The trade-off in this task is between flexibility to serve the data flows without wasting resource (e.g. padding) and TFCS size. The listing of TFCSs for each S-CCPCH for both schedulers under both alternatives for channel-mapping derivation is not apparently feasible within the space limitations of this paper. The interested reader is referred to the appendices of Reference [22] for a detailed list of TFCSs for all simulation scenarios addressed in the context of the EU Satin project.

Note that FACHs of 64 kb/s can accommodate both audio and video streaming flows. Resource sharing amongst flows with the same rate requirements increases the resource utilization [23] for a given load but requires larger TFSs for the respective channel. These have to be broad enough to capture the packet-level behaviour of both types of sources that are usually significantly different, without resorting to excessive padding.

4.4. Simulation metrics

We use two types of metrics in evaluating the packet scheduling schemes:

- *User-centric*: these express the quality of service the flows obtain from the scheduler. Delay and delay variation are the performance indicators for streaming services, whereas for download services we examine if the committed mean rate is preserved at long term.
- *Network-centric*: they express how efficient the scheduler is with respect to the system resources (power, bandwidth). Utilization and padding ratio are the main ones. In Section 5.4, we also consider the efficiency of the scheduler power allocations under the two options for the channel mapping derivation, namely bin-packing and power-aware packing.

5. PERFORMANCE EVALUATION

Illustration of all metrics and aspects addressed in Reference [22] within the space limitations of this paper is clearly impossible. Nevertheless, we select indicative illustrations that illuminate the main outcome of the simulation study and support the discussion that follows.

5.1. Delay and delay variation at S-RAN

The general trend with the MLPQ-based scheme is in agreement with the well-reported behaviour of the ancestor scheme in wired networks: low-priority channels feature high delay values per packet and also high variation of these values (Tables V and VI). Although data carried over these FACHs arrive with a CBR rate, their emission follows less regular patterns: data are buffered for some interval and then are sent in bursts, when the channel is freed by higher priority services. The over-the-air rate of these FACHs effectively oscillates between zero and higher rates, to the extent allowed by the TFS of these channels. For example, in the case of FACH 4 at S-CCPCH 5 the transport channel is not allowed to forward data for 70% of the simulation time (equal to the mean duration of data streaming services) but when it transmits, it does so by using TBS sizes much higher than the ones corresponding to its mean rate, as shown in Figure 8. Nevertheless, from the service point of view, the short-term burstiness does not introduce problems, since there are no packet-level QoS requirements for download services, apart from the provision of a constant rate over longer-than-TTI time intervals (Figure 9).

The additional flexibility in comparison with the standard MLPQ-based scheme with exhaustive service is due to the TFCS, which allows, compromising the privileged service, higher-priority flows obtain with better support of lower-priority ones. However, the penalty is related to the larger TFCS size that in some cases approaches the upper constraints defined by standards (128 TFCs per code channel for the 384 kbps terminal class [6, Chapter 6]).

Results obtained from the WFQ-based PS showed that when time-sharing of resource relies only on the bearer weights (rates) of flows, there is significant delay/jitter degradation

Table V. Packet delay at RLC buffers—MLPQ-based scheduler, power-aware packing.

	Mean (s)	Standard dev. (s)	Median (s)	90th percentile (s)	99th percentile (s)
S-CCPCHs 1–2					
FACH 1	0.0297	0.0235	0.0293	0.0374	0.0398
FACH 2	0.0246	0.0247	0.019	0.039	0.059
FACH 3	0.0237	0.0239	0.019	0.039	0.059
FACH 4	0.0229	0.0230	0.019	0.039	0.039
FACH 5	0.0147	0.0147	0.01	0.03	0.05
FACH 6	0.1187	0.1187	0.0933	0.24	0.4533
S-CCPCH 3					
FACH 1	0.03	0.0057	0.03	0.038	0.0398
FACH 2	0.0929	0.0505	0.0831	0.1591	0.2373
FACH 3	0.0936	0.0479	0.0873	0.1573	0.2175
FACH 4	1.9892	2.0671	1.3	4.68	10.1
S-CCPCH 4					
FACH 1	0.0550	0.0160	0.0545	0.0744	0.1069
FACH 2	0.1058	0.0448	0.1066	0.166	0.2266
FACH 3	1.4216	1.119	1.16	3.06	3.98
S-CCPCH 5					
FACH 1	0.0345	0.015417	0.03	0.0571	0.07
FACH 2	0.0915	0.053656	0.08	0.166	0.2333
FACH 3	0.0598	0.044035	0.0521	0.1215	0.1864
FACH 4	4.1137	2.303116	3.5466	7.94	8.926
S-CCPCH 6					
FACH 1	0.0796	0.0462	0.07	0.1457	0.2066
FACH 2	0.0766	0.0455	0.066	0.14	0.2066
FACH 3	1.8847	1.0191	1.9933	3.1066	3.733
S-CCPCHs 7–8					
FACH 1	0.0571	0.0334	0.048	0.1066	0.1631
FACH 2	2.5621	0.9737	2.776	3.416	4.74

performance for the flows with the highest QoS requirements, namely the streaming ones. Therefore the WFQ-based PS per S-CCPCH proceeds as follows: bearers of different QoS classes are served with strict priority, and the actual WFQ scheme, using time stamps as described in Section 3.3.1, is eventually applied to flows of the same QoS class.

The scores of the WFQ-based scheduler, with regard to both delay (Table VII) and delay variation (Table VIII), are worse than those of the MLPQ-based scheduler. There is a clear performance lag in terms of both mean and percentile values, which is independent of the CTCH/FACH type, i.e. whether it carries streaming or download service flows. Rather than implying an inherent superiority of the MLPQ-based scheduler over the WFQ-based scheduler, the results suggest that the scheduler TFCS is far from optimum and call for further experimentation before definite conclusions are derived upon the appropriateness of the WFQ-based scheduler.

Table VI. Packet delay variation at RLC buffers—MLPQ-based scheduler, power-aware packing.

	Mean (s)	Standard dev. (s)	Median (s)	90th percentile (s)	99th percentile (s)
S-CCPCHs 1–2					
FACH 1	0.0016	0.0036	0.0026	0.0068	0.0149
FACH 2	0.0113	0.0151	0.0234	0.04	0.04
FACH 3	0.0079	0.0098	0.0112	0.04	0.04
FACH 4	0.0079	0.0098	0.0109	0.02	0.02
FACH 5	0.0095	0.0127	0.0105	0.02	0.04
S-CCPCH 3					
FACH 1	0.0095	0.0020	0.01	0.01	0.0134
FACH 2	0.0351	0.0259	0.0285	0.06	0.1095
FACH 3	0.0351	0.0253	0.0308	0.06	0.1004
S-CCPCH 4					
FACH 1	0.0115	0.029	0.01	0.0128	0.0354
FACH 2	0.0451	0.0062	0.04	0.0733	0.1533
S-CCPCH 5					
FACH 1	0.0129	0.0092	0.0133	0.0257	0.0466
FACH 2	0.0386	0.0414	0.02	0.1066	0.1867
FACH 3	0.0345	0.0294	0.03	0.07	0.1653
S-CCPCH 6					
FACH 1	0.0285	0.0309	0.0143	0.0533	0.1667
FACH 2	0.0290	0.0312	0.0143	0.0533	0.1667
S-CCPCHs 7–8					
FACH 1	0.0161	0.0167	0.0133	0.0266	0.1036

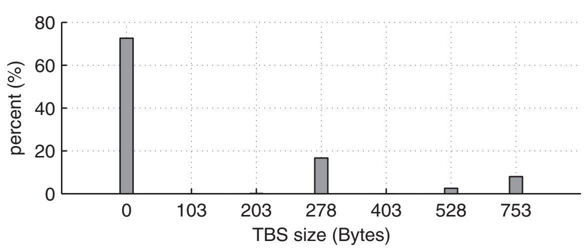

Figure 8. Transport block set size distribution for FACH 4 at S-CCPCH 5-TBS size includes RLC/MAC headers.

5.2. Fairness

In general, some notion of fairness is desirable among flows of the same traffic handling priority, i.e. two streaming flows should not see much difference in the obtained performance. In the case of the MLPQ-based PS, an enhancement was made to the scheduler so that the order of serving FACHs of the same traffic handling (TH) priority alternates cyclically on a TTI basis. Apparently, this is a way to smoothen performance discrepancies, although the actual delay and

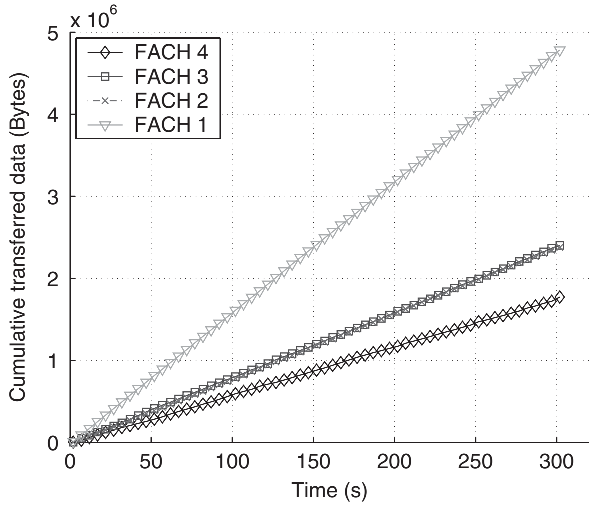

Figure 9. Per FACH cumulative transferred data on S-CCPCH 5.

jitter values are still heavily dependent on the behaviour of the flow at TTI-scale. The scores of the scheduler regarding fairness are better in the power-aware packing case than in the bin-packing case. The reason is that the former tends to map flows of similar rate onto the same code channel [9]. Then the combination of similar TFs with the cyclic alternation of the serving order of FACHs of the same traffic handling priority can lead to similar performance for the flows; in other words, the tuning of the TFCS is easier. Nevertheless, the potential to achieve similar performance in terms of jitter is hard-limited by the actual packet-level dynamics of the flows, namely burstier flows feature longer upper tails in the jitter cumulative distribution function (similar to what is shown later in Section 5.5).

Contrary to the MLPQ-based scheme, in the WFQ-based scheme it makes little difference whether the underlying mapping is power-aware or not. In general, the fairness scores of the two schemes are similar, although in the case of the MLPQ-based scheme they appear to be more sensitive to the actual TFCS selection.

5.3. Channel utilization and padding ratio

Figure 10 plots the variation of the S-CCPCH utilization with time for the MLPQ-based scheduler under the bin-packing scenario. The scheduler manages to achieve throughput close to the optimum in almost all channels. Padding is negligible, under 1% for all S-CCPCHs (Figure 11). The penalty for this efficiency is the size of the TFCS: 41, 41, 49, 86, 92, 92 for the physical channels 1–6, respectively, which is much larger than the usual TFCS size [24]. In the power-aware packing scenario, we managed to get similar performance, namely utilization close to unity with minimum padding, with smaller TFCSs. The inherent tendency of this mapping algorithm to pack together services of the same rate together with the cyclical alternation of the FACH serving order simplifies the derivation of suitable TFCs.

Table VII. Packet delay at RLC buffers—WFQ-based scheduler, power-aware packing.

	Mean (s)	Standard dev. (s)	Median (s)	90th percentile (s)	99th percentile (s)
S-CCPCHs 1–2					
FACH 1	0.1096	0.2198	0.044	1.277	1.277
FACH 2	0.0531	0.0404	0.04	0.28	0.28
FACH 3	0.0355	0.0429	0.02	0.26	0.26
FACH 4	0.0306	0.0393	0.02	0.26	0.26
FACH 5	0.0299	0.0380	0.02	0.24	0.24
FACH 6	9.2218	5.5558	9.187	18.707	18.707
S-CCPCH 3					
FACH 1	0.2146	0.2727	0.117	1.499	1.499
FACH 2	0.1886	0.2396	0.098	1.075	1.075
FACH 3	0.1825	0.2251	0.0841	1.154	1.154
FACH 4	5.3742	2.7037	5.56	10.48	10.48
S-CCPCH 4					
FACH 1	0.1753	0.1823	0.11	0.902	0.902
FACH 2	0.1228	0.0943	0.0933	0.46	0.46
FACH 3	4.5257	4.3799	2.42	13.64	13.64
S-CCPCH 5					
FACH 1	0.1411	0.1982	0.091	1.226	1.226
FACH 2	0.0974	0.0562	0.087	0.3	0.3
FACH 3	0.0779	0.0512	0.067	0.26	0.26
FACH 4	16.773	10.5499	15.367	33.68	33.68
S-CCPCH 6					
FACH 1	0.0952	0.0543	0.09	0.246	0.246
FACH 2	0.0751	0.0444	0.067	0.206	0.206
FACH 3	22.575	12.826	23.1734	43.387	43.387
S-CCPCHs 7–8					
FACH 1	1.426	1.307	0.744	3.545	3.545
FACH 2	13.489	6.33	15.096	24.02	24.02

The results derived with the WFQ-based scheme are again worse than those obtained with the MLPQ-based scheme and confirm that the derivation of the TFCS in the considered multiplexing scenarios is a bit of an art. Although the padding ratio it introduces is consistently higher (Figure 13), the WFQ-based scheduler achieves lower physical channel utilization than the MLPQ-based scheduler (Figure 12). Moreover, the TFC sets of the WFQ-based scheduler are even larger than the ones tested with the MLPQ-based scheme. For the channel mapping derived via power-aware packing the size ranged from 27 up to 109, whereas in the bin-packing scenario, the TFCS size for all physical channels exceeded 100.

5.4. Power-related considerations

The link-level simulations [21] indicated that performance, in terms of the required E_b/N_0 in order to achieve a target block error ratio (BLER), improves with higher transport

Table VIII. Packet delay variation at RLC buffers—WFQ-based scheduler, power-aware packing.

	Mean (s)	Standard dev. (s)	Median (s)	90th percentile (s)	99th percentile (s)
S-CCPCHs 1–2					
FACH 1	0.1432	0.216	0.1000	0.28	1.12
FACH 2	0.06	0.0232	0.0600	0.08	0.14
FACH 3	0.06	0.0287	0.0600	0.10	0.14
FACH 4	0.06	0.0202	0.0600	0.08	0.14
FACH 5	0.06	0.0196	0.0600	0.08	0.14
S-CCPCH 3					
FACH 1	0.132	0.1974	0.1	0.24	1.06
FACH 2	0.144	0.206	0.1	0.28	1.24
FACH 3	0.064	0.103	0.04	0.10	0.64
S-CCPCH 4					
FACH 1	0.0649	0.0971	0.04	0.1	0.5
FACH 2	0.0652	0.0574	0.06	0.14	0.26
S-CCPCH 5					
FACH 1	0.0655	0.102	0.04	0.0257	0.6
FACH 2	0.0603	0.0649	0.04	0.1066	0.28
FACH 3	0.0302	0.0336	0.02	0.07	0.16
S-CCPCH 6					
FACH 1	0.0321	0.0287	0.02	0.06	0.14
FACH 2	0.0303	0.0282	0.02	0.06	0.14
S-CCPCHs 7–8					
FACH 1	0.0178	0.0143	0.02	0.04	0.04

block (TB) size,[‖] since larger TBs interpret into larger turbo-coded packets, hence larger internal interleaver and better turbo-code performance. In light of this result, there are two main approaches in setting the per-physical channel transmit power.

One option is to adjust the power upon the data flow arrival/termination events. Let $(E_b/N_0)^i_{\text{av}}$ be the E_b/N_0 requirement for the TB corresponding to the mean rate R^i_{av} of the ith FACH mapped on a given S-CCPCH. Then the transmit power of the physical channel can set according to some reference E_b/N_0 value, $(E_b/N_0)_{\text{ref}}$, which is a function of the E_b/N_0 requirements of all FACHs it multiplexes. For example, the power could be set according to the worst-case E_b/N_0 value, namely

$$(E_b/N_0)^{\text{ref}}_{\text{av}} = \max_i \left((E_b/N_0)^i_{\text{av}}\right) \tag{6}$$

Then the power setting will remain fixed and the scheduler may readjust it when a new flow is mapped on this S-CCPCH or one of the existing flows is terminated. In both cases the power setting will change if these events generate a change of the $(E_b/N_0)_{\text{ref}}$.

[‖] The performance improves monotonically for TBS sizes up to 5000 bits—maximum TB size allowed by 3GPP specifications. Larger TBS sizes yield two transport blocks of smaller size, hence performance will equal that of TBS size/2.

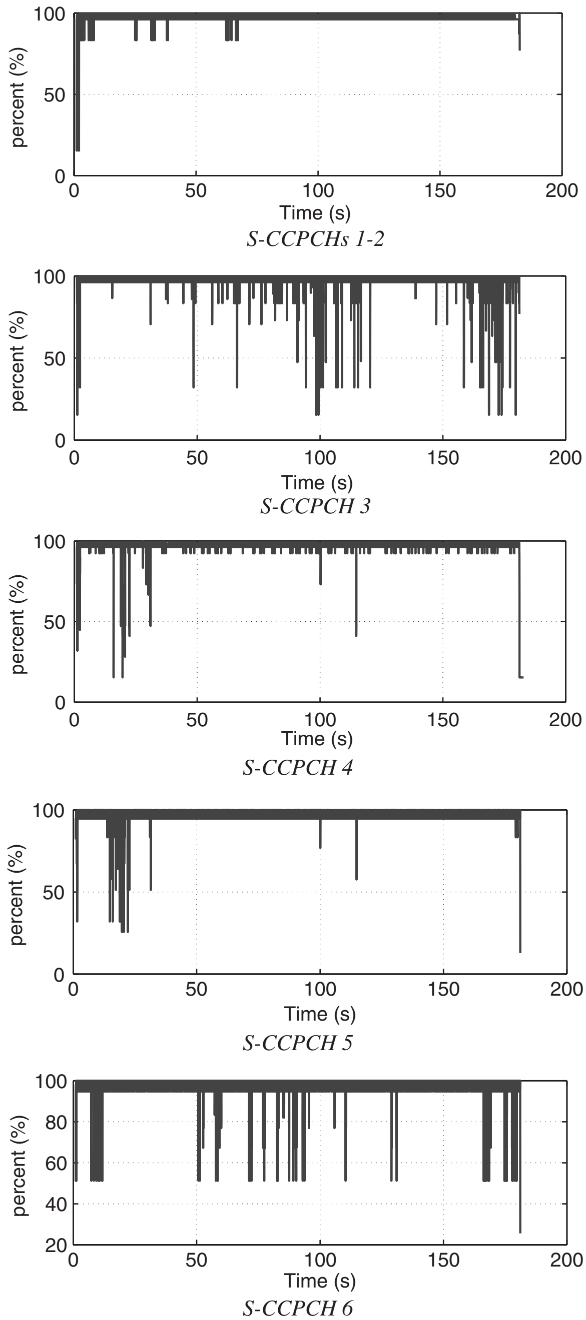

Figure 10. Per S-CCPCH utilization versus time—MLPQ-based scheme, bin-packing.

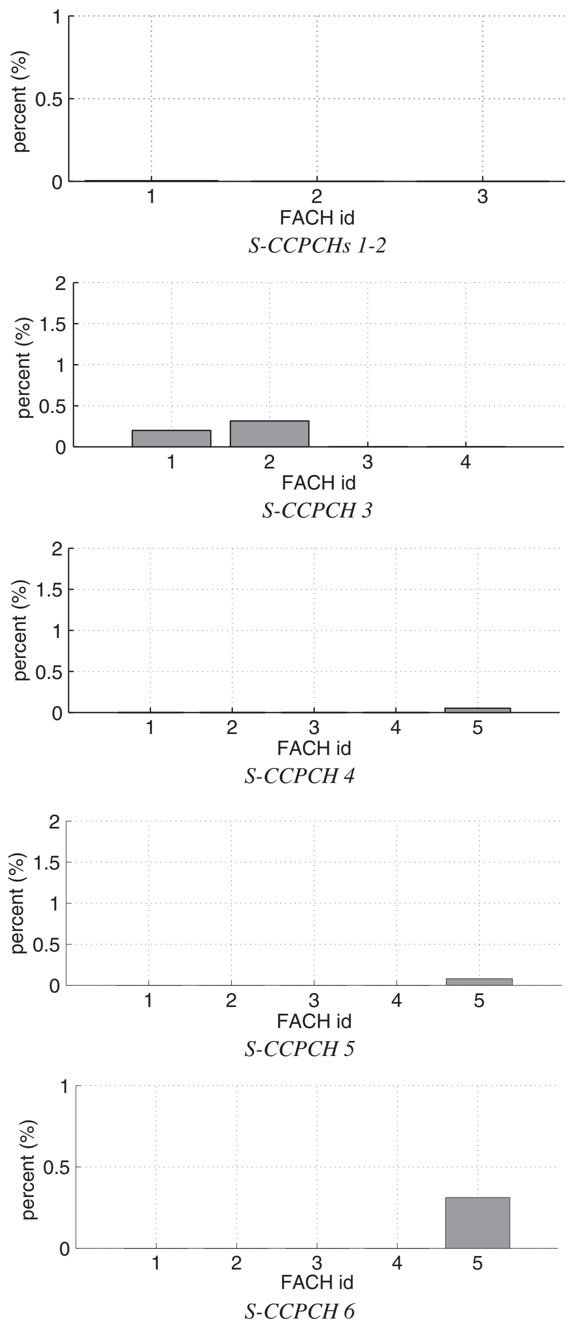

Figure 11. Per FACH padding ratio—MLPQ-based scheme, bin-packing.

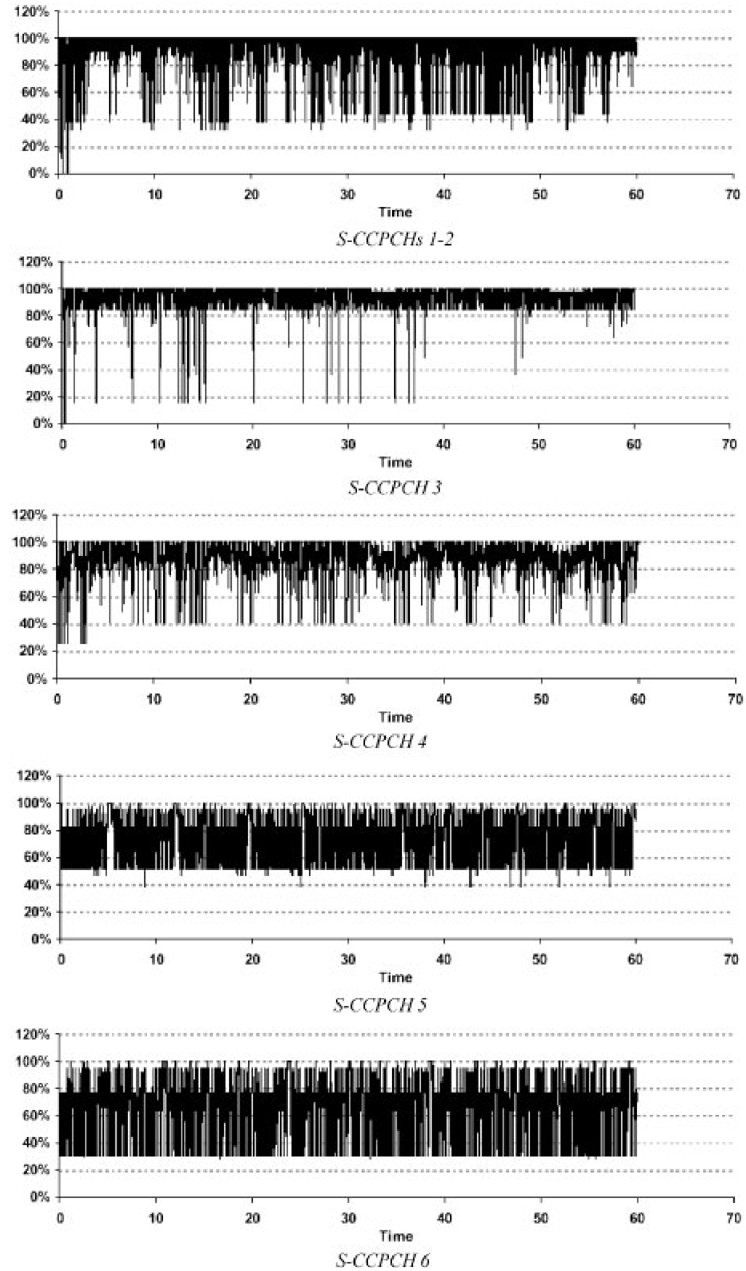

Figure 12. Per S-CCPCH utilization versus time—WFQ-based scheme, bin-packing.

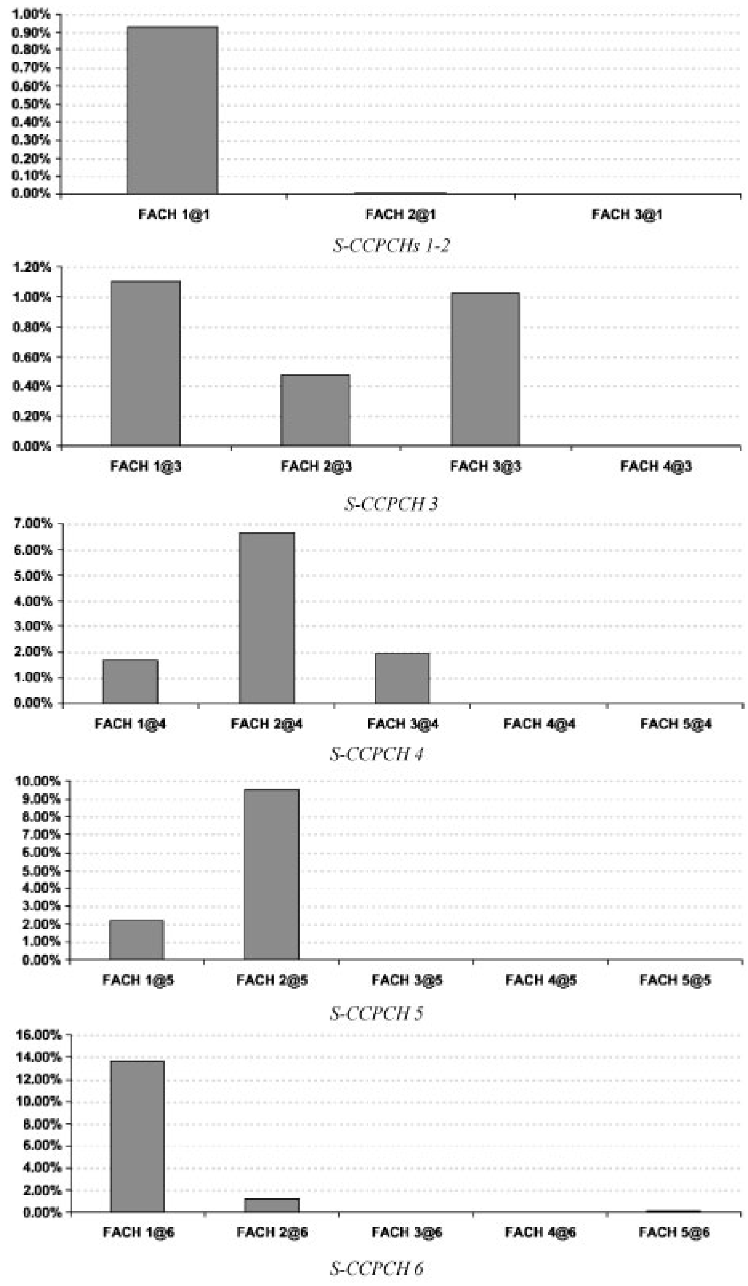

Figure 13. Per FACH padding ratio—WFQ-based scheme, bin-packing.

Contrary to this 'static' approach, the scheduler might also change the transmit power at TTI level. If $(E_b/N_0)^i_{\rm in}$ are the E_b/N_0 requirements related to the TBS chosen for FACH i by the scheduler in a given TTI, then the power may be set as a function of these values. A worst-case

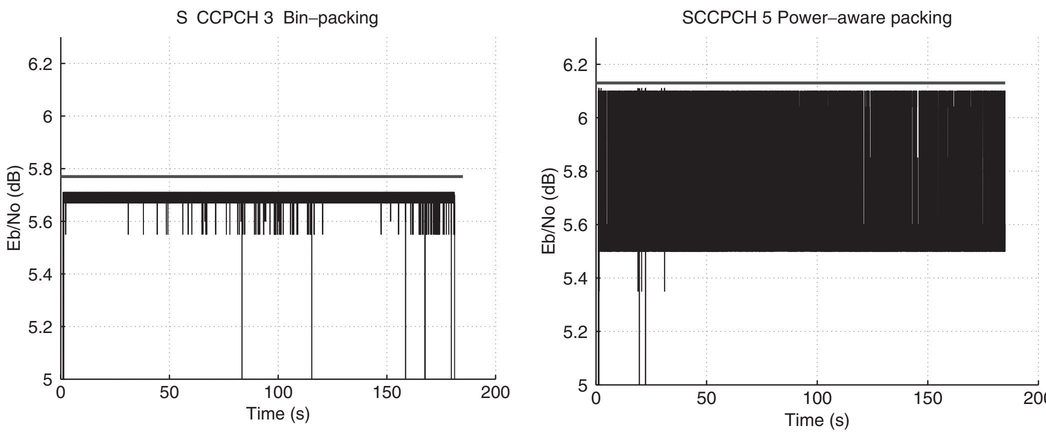

Figure 14. E_b/N_0 requirements arising from MLPQ-based PS versus time with static power setting.

Table IX. Comparison of the two options for physical channel power adjustment.

S-CCPCH 3 (bin-packing)		*S-CCPCH 5 (power-aware packing)*	
$(E_b/N_0)_{\mathrm{av}}^{\mathrm{ref}}$	6.13 dB	$(E_b/N_0)_{\mathrm{av}}^{\mathrm{ref}}$	5.77 dB
$(E_b/N_0)_{\mathrm{in}}^{\mathrm{ref}}$	5.6 dB	$(E_b/N_0)_{\mathrm{in}}^{\mathrm{ref}}$	5.48 B
$(E_b/N_0)_{\mathrm{max}}$	6.13 dB	$(E_b/N_0)_{\mathrm{max}}$	5.71 dB

power adjustment in this case would correspond to

$$(E_b/N_0)_{\mathrm{in}}^{\mathrm{ref}} = \max_i ((E_b/N_0)_{\mathrm{in}}^i) \tag{7}$$

and would be different each TTI.

Figure 14 compares the two options on the basis of the E_b/N_0 requirements they generate. The per-TTI $(E_b/N_0)_{\mathrm{in}}^{\mathrm{ref}}$ values correspond to the MLPQ-based scheme resource allocations. The figure also reports the maximum and the *effective* E_b/N_0. The latter is an approximation of the statistical mean of the E_b/N_0 requirements of the code channel. It is estimated as:

$$(E_b/N_0)_{\mathrm{eff}} = \sum_{j \in \mathrm{TFCS}} f_j \cdot (E_b/N_0)_j \tag{8}$$

where f_j is the weight of TFC j included in the TFCS, estimated as the ratio of the number of appearances of TFC j over the total number of TFCs selected by the scheduler during its operation. The E_b/N_0 for each TFC j is the worst-case E_b/N_0, i.e. the maximum E_b/N_0 requirement amongst all services for a given TTI, determined on the basis of the individual TBS selection of the transport channels.

The effective E_b/N_0 requirement is lower than the rather conservative estimations of AC, which are plotted with a horizontal solid line in Figure 14 and are also reported in Table IX, with both channel mapping methods, namely bin-packing and power-aware packing. Potential feedback from the PS back to AC could help update the AC awareness of resource consumption and lead to better use of system capacity. Alternatively, the additional power margins can be interpreted into higher reception quality at the user side. It comes out that the decisive factor from a power saving point of view is the TFCS and the respective TB sizes that are made available to the scheduler rather than the way the mapping is performed (power-aware or unaware). In fact, the proposed packet schedulers confirm the challenging task of determining optimized TF/TFCs, and more particularly the relevance of TBS size thresholds: the TF/TFCs should not include TBS sizes smaller than some minimum threshold, so as to relax E_b/N_0 requirements and save system power but at the same time should provide values small enough to achieve better physical channel utilization and meet the rate requirements of the lowest priority services.

5.5. *Impact of packet-level dynamics*

The measured statistics were obtained under certain modelling assumptions. It was deemed interesting to investigate the sensitivity of these assumptions upon these modelling assumptions. For example, there was no specific input from scientific literature favouring the choice of the ON–OFF model for audio steaming; it was selected mainly due to its simplicity and the associated easiness in controlling the traffic dynamics on the basis of a couple of parameters.

On the contrary, the audio streaming model in Reference [19] has taken a structural modelling approach and relies on measurements of RealAudio traffic. It is reported there that the flows appear to have a constant bit rate when the latter is measured over scales of seconds or tens of seconds but exhibit burstiness over shorter intervals. In fact, packets are sent in bursts following idle intervals of the order of second(s). These intervals were found to be integer multiples of a specific time interval, whose value was attributed to the multitasking nature of the operating system.

It becomes obvious from Figure 15 that the impact of the model is anything but negligible. There are differences in the delay D and jitter D_v values approaching two orders of magnitude.

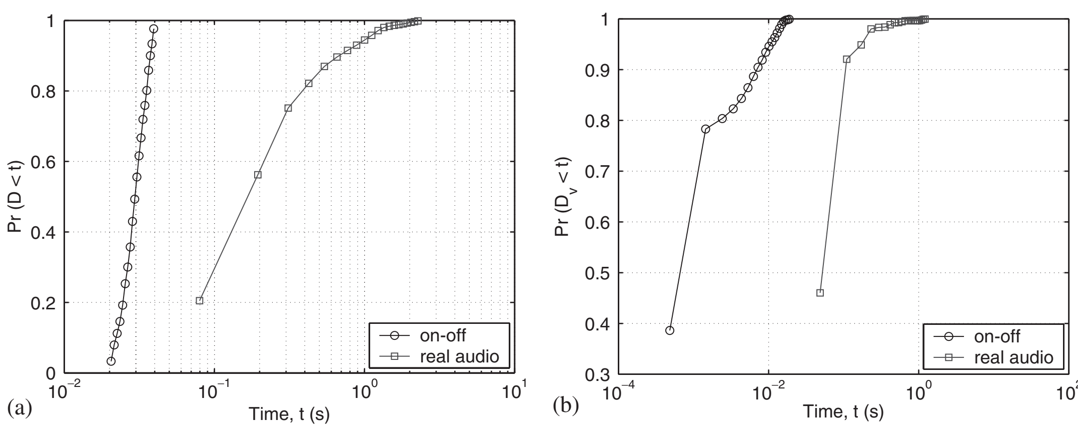

Figure 15. Comparison of delay and delay jitter between the exponential on-off model and the RealAudio model (FACH 1 at S-CCPCH 1, bin-packing based mapping). (a) Delay (b) Jitter.

These differences are the results of the radically different packet-level dynamics of the two flows (models) rather than the outcome of inefficient, non-optimized scheduling.

6. CONCLUSIONS

In this work, we addressed the packet scheduler role in the delivery of point-to-multipoint services within a satellite radio interface relying on the downlink common channels of the WCDMA radio access scheme. Given the transport channel choice (FACH), the time scheduling of the different FACHs that have been mapped to a single S-CCPCH is the major task of the packet scheduler. We proposed adaptations of two schemes that are known from the context of wired networks for this task, an MLPQ-based scheme and a WFQ-based scheme.

The evaluation of the two proposed packet schedulers confirmed the challenging task of determining optimized TF/TFCs, and more particularly the relevance of TBS size thresholds in meeting the rate requirements of all services and achieving high physical channel utilization, whilst preserving the power resources of the system.

Regarding fairness between flows of same QoS class or physical channel utilization, it makes little difference for each PS scheme whether the mapping is power-aware or not, although the tuning of the TFCS appears to be easier in the pure bin-packing case with the MLPQ-based PS. The WFQ-based PS exhibits high sensitivity to the TFCS selection process and the packet-level dynamics of the flows in many multiplexing cases have not allowed the significant reduction of the individual CTCH/FACH TF range.

Equally important is the impact of the TFCS on the power consumption of the system. On the contrary, the actual way to perform the mapping (power-aware or not) seems to be less significant. In summary and irrespective of the PS scheme, the optimization of the system capacity/throughput depends on the cautious trade-off between power saving and multiplexing effectiveness.

APPENDIX A: THE BIN-PACKING AND POWER-AWARE PACKING METHODS FOR CHANNEL MAPPING

We describe two methods for mapping the service data flows, namely the logical/transport channel pairs, on physical channels. The number of available S-CCPCHs M and their maximum capacity c, or a rough estimation of theirs, are derived *a priori* from link budget exercises and link-level simulation input. The link budgets for the indirect case dictated a maximum supported bit rate of 384 kbps, corresponding to SF 8. Allowing codes for the broadcast channel and the announcement channel, the available S-CCPCHs at SF 8 are 6–7. Few physical channels of smaller SF (resp. higher rate) are preferred over more channels of higher SF (resp. lower rate) so that multiplexing gain is derived when multiple FACHs are mapped onto them.

There are two alternatives for this mapping:

One is to ignore the power requirements (E_b/N_0) of individual services. Then a mathematical formulation of the problem could be:

$$\begin{aligned} &\text{minimize} \quad z = \sum_{j=1}^{N} y_j \\ &\text{subject to} \quad \sum_{i=1}^{N} R_i \cdot x_{ij} \leqslant c \cdot y_j, \quad j \in \{1 \ldots N\} \\ &\qquad\qquad \sum_{j=1}^{N} x_{ij} = 1, \quad i \in \{1 \ldots N\} \end{aligned} \tag{A1}$$

where $y_j = 1$ if S-CCPCH j is used or 0 otherwise and $x_{ij} = 1$, if service (FACH) i is assigned to S-CCPCH j, 0 otherwise. This is an instance of the bin-packing problem: the CTCH/FACHs are the items that have to be packed into the minimum possible number of bins, which correspond to the S-CCPCHs. A feasible solution of the problem corresponds to cost values z less than or equal to the number of bins M. Both approximate and exact algorithms are available for the solution of this problem; given the rather small number of S-CCPCHs, computation efficiency does not pose significant constraints [25].

The second option is to take into consideration the power requirements E_b/N_0 of the individual services into what we call 'power-aware packing'. We can then apply a variation of the bin-packing algorithm to derive a mapping that minimizes power waste, in that it groups services of similar power requirements to each S-CCPCH. The E_b/N_0 requirement is a function of the transport block (TB) size most frequently used. The per-service E_b/N_0 requirement in the power-aware packing is the one corresponding to the service guaranteed rate.

In comparison with (A1), only the objective function changes:

$$\begin{aligned} &\text{minimize} \quad z = \sum_{j=1}^{N} y_j \cdot (E_b/N_0)_j, \quad j \in \{1 \ldots N\} \\ &\text{where} \quad (E_b/N_0)_j = \max_k \ \{(E_b/N_0)_k, \ k : x_{kj} = 1\} \end{aligned} \tag{A2}$$

Although the objective function in this case is non-linear and less conventional, adaptations of the approximate algorithms for the classical bin-packing problem [25] can be used to obtain an approximate solution of the problem.

APPENDIX B: TRAFFIC MIX CONSIDERED FOR THE PACKET SCHEDULER EVALUATION

Table B1 outlines the traffic load produced at system (beam) level from streaming services. The system is studied in its early operational years and the subscriber base consists of two types of users, typical and business users, the latter having higher interest in services such as software download, news trailers and location-based services.

Table B2 describes the demand for download services. The characterization of download services is different from streaming services [9]. These services are transmitted cyclically on data carousels, which are transmitted continuously over the air, and their frequency of appearance depends on their popularity, expressed numerically in terms of demand probability distribution.

Table B1. Streaming service traffic mix.

Service type	Guaranteed bit rate (kbps)	System (beam)-level request rate (per hour)	Load (kbps)
Audio broadcast (streaming)	32	9.99	59.76
	64	6.21	
Video broadcast (streaming)	64	5.58	90.96
	128	3.803	
	256	0.968	
Location-based services	16	61.5	49.2

Table B2. Demand for download services.

Service type	Service request rate (per hour, system level)	Normalized demand probability per service type
"Rich" video/audio information	51 000	0.229265
Pre-stored movie on demand	3900	0.017532
Pre-stored video clips on demand	13 500	0.060688
Pre-stored radio on demand	27 000	0.121375
Pre-stored music on demand	25 500	0.114633
Software download	35 550	0.159811
Webcasting	66 000	0.296696

ACKNOWLEDGEMENTS

The authors would like to thank all colleagues who contributed to the EU IST SATIN project and provided inputs to this paper. Thanks are also due to the anonymous reviewers of this work for their detailed comments on both the content and the presentation of the paper.

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