Satellite Radio Interface and Radio Resource Management Strategy for the Delivery of Multicast/Broadcast Services via an Integrated Satellite-Terrestrial System

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ABSTRACT

A variety of hybrid systems combining third-generation mobile communication networks with broadcast systems have been proposed for the delivery of multimedia broadcast multicast services (MBMS) to mobile users. The article discusses one of these alternatives, which involves the use of a geostationary satellite component for MBMS delivery. In particular, it proposes a radio access scheme for the satellite component of the system that features maximum commonalities with the standardized T-UMTS WCDMA-based interface. The ultimate advantage of this approach is more efficient delivery of MBMS as far as the mobile network operator is concerned. The required adaptations at the interface layers are described, and the radio resource management strategy that fulfills the particular requirements of the satellite system is presented.

INTRODUCTION

The multimedia concept is strongly embedded within the forthcoming third-generation (3G) mobile communication networks. The introduction of more bandwidth-demanding multimedia services, however, raises concerns related to the additional traffic load produced and the network capacity required. The scarcity of extra 3G spectrum requires very careful radio network planning and system design to ensure that new broadband services will not result in the interference-limited system suffering frequent outage events.

The introduction of the broadcast/multicast mode of service delivery in terrestrial mobile networks is one way to address these concerns. The ongoing standardization work within the 3G Partnership Project (3GPP) multimedia broadcast multicast services (MBMS) framework is progressing in this direction. More drastic approaches rely on synergies between 3G cellular networks and broadcast systems. The latter relieve 3G networks from point-to-multipoint services, allowing them to devote their full capacity to more profitable point-to-point services.

The inherent broadcast capabilities of satellites make them an attractive candidate platform for the provision of point-to-multipoint services. Their close synergy with terrestrial mobile networks has advantages for both mobile and satellite operators. Investment savings on R&D, overall system deployment cost reduction, and the potential to penetrate a broader market than the vertical niche markets mobile satellite systems typically address are the main benefits for satellite operators. Terrestrial mobile network operators, on the other hand, may find synergistic solutions (as opposed to standalone T-MBMS) increasingly attractive as the targeted average revenue per user decreases [2].

This article describes a satellite radio access scheme designed for efficient support of MBMS

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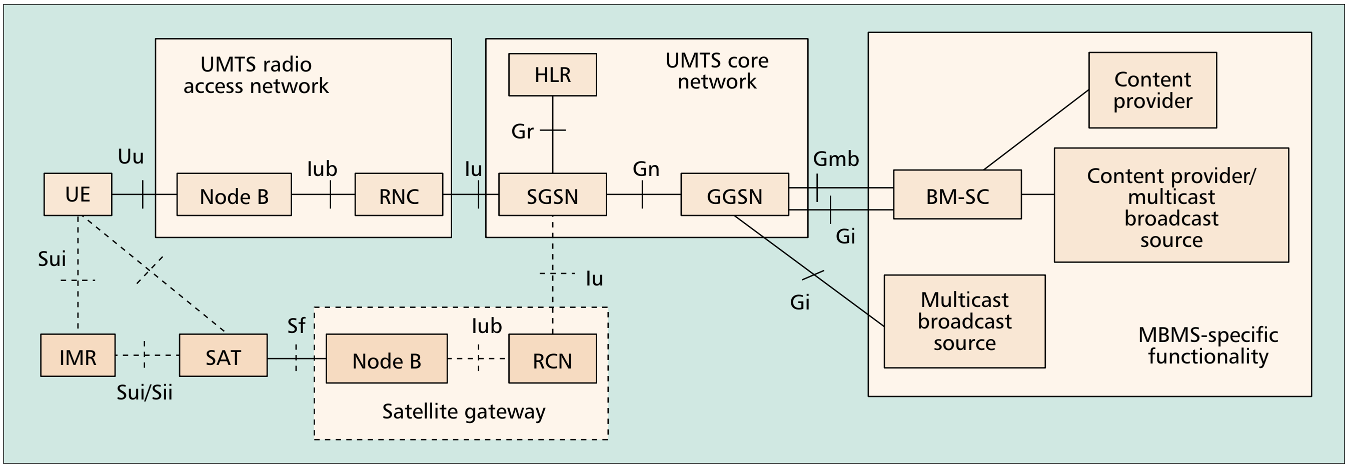

Figure 1. *The proposed satellite radio access network as an alternative radio access network and its position within the 3GPP MBMS architecture. The satellite-specific entities and interfaces are depicted with dark color and dashed lines, respectively.*

via close synergy with terrestrial Universal Mobile Telecommunications System (T-UMTS), drawing on work carried out within the European Union (EU) SATIN[1] project. The scheme features maximum commonalities with the UMTS terrestrial radio access frequency-division duplex (UTRA FDD) air interface standardized within the 3GPP initiative, which is widely known as wideband code-division multiple access (WCDMA). The main benefits of this approach lie in the mobile terminal side. The use of the same waveform over the satellite radio interface enables maximum reuse of terminal hardware for both T-UMTS and satellite UMTS (S-UMTS) modes with significant advantages in terms of terminal size, power consumption, and, eventually, cost.

THE SYSTEM ARCHITECTURE CONCEPT

The satellite system under consideration is effectively unidirectional. The space segment consists of a geostationary satellite that covers the EU area with several beams corresponding to different linguistic groups. Despite the advantages of onboard switching for multicast traffic treatment, the satellite features a transparent digital processing payload with multiple beams. This choice provides the desired flexibility in updating/enhancing the system throughout its life and is accompanied by reduced technology and investment risk.

The satellite system component is integrated within the packet-switched domain of UMTS. In Fig. 1 it is positioned with respect to the reference MBMS architecture [1]: it may be regarded as an alternative radio access network (RAN), the UMTS satellite RAN (USRAN), which interfaces with the UMTS core network, namely the General Packet Radio Service (GPRS) backbone. The two USRAN functional nodes that are almost always physically separated in T-UMTS, the radio network controller (RNC) and Node B, are collocated in the satellite gateway. The interfaces of the USRAN with the UMTS core network and user equipment (UE), and those within the USRAN draw on the standard Iu, Uu, and Iub interfaces, respectively. A return link is provided via the terrestrial mobile networks (T-UMTS). Central to the system concept is the use of terrestrial gap fillers, hereafter called *intermediate module repeaters* (IMRs).

THE INTERMEDIATE MODULE REPEATER

The introduction of intermediate modules (gap fillers) in the system architecture has been regarded as mandatory in order to overcome the inability of mobile satellite systems to provide adequate urban and indoor coverage. This inability has been regarded as one of the main reasons for the failure of satellite personal communication networks (S-PCNs) to penetrate the mass consumer market.

The actual functionality of gap fillers within the proposed integrated system can vary from the simple satellite signal amplification to the full set of UMTS Node B and RNC functions [3]. In general, the transfer of a smaller or larger subset of Node B/RNC functions from the satellite gateway to the intermediate modules improves the responsiveness of the system to the link quality variations and facilitates short-term radio resource management mechanisms such as power control or packet scheduling. However, it increases module complexity and cost; it further assumes that the geostationary satellite link can be deemed an acceptable transport medium for support of the Iu or Iub interfaces (Fig. 1), despite its considerable latency and channel errors. On the other hand, limiting the gap filler functionality to the minimum of signal amplification minimizes the module complexity and cost, and does not necessitate standards modifications. Also taking into consideration that the point-to-multipoint nature of services limits the relevance of power control and "channel-state-dependent" packet scheduling, the second choice was retained as a reference in the proposed system architecture.

Nevertheless, IMRs pose some additional requirements on the UE. Each IMR, collocated with a T-UMTS Node B, retransmits a replica of the transmitted satellite signal in the same frequency band through a terrestrial multipath channel. The composite signal differs significant-

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[1] *EU Information Society Technologies (IST) Satellite UMTS IP-Based Network (SATIN), http://www.ist-satin.org*

The minimization of the terminal complexity is one of the key objectives of this integrated architecture concept. Given that the terminal is satellite receive-only, significant savings are already achieved, since the power-demanding elements needed for uplink transmission towards the satellite are omitted.

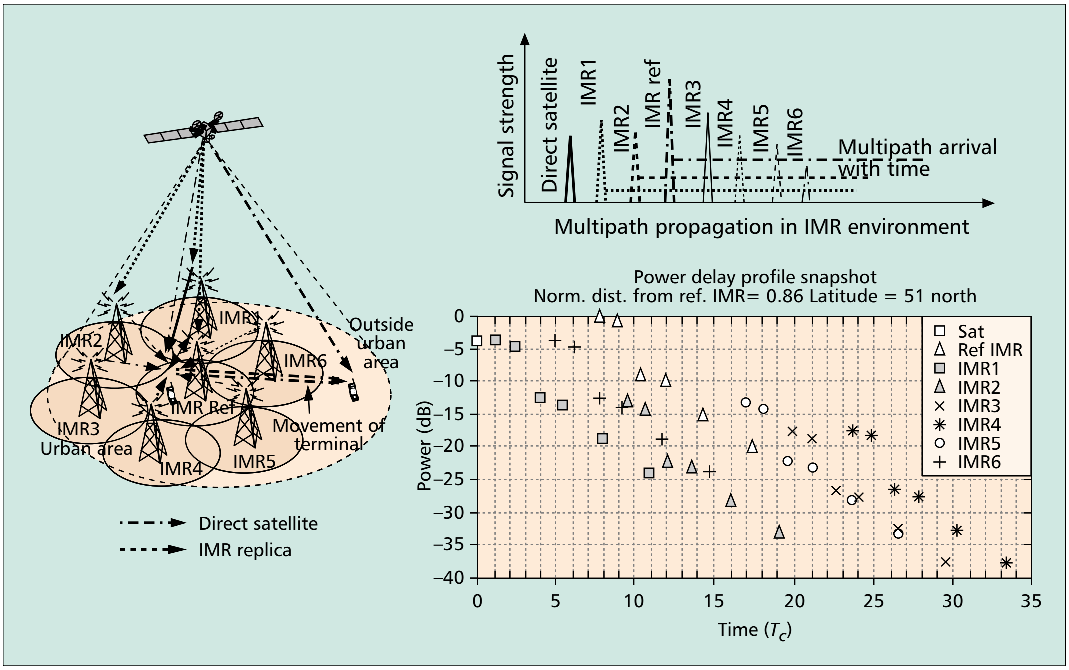

Figure 2. *IMR layout and artificial multipath due to the introduction of IMRs. The delay spread, normalized in chip duration time units* (T_c)*, is much larger than in T-UMTS.*

ly from the signal received by different Node Bs in T-UMTS. In that case, the radio transmissions from all Node Bs other than the one to which the terminal is attached carry different data, use different scrambling codes, and appear as interference to the useful signal at the receiver. On the contrary, IMR transmissions are asynchronous replicas of the same satellite signal because of the different propagation path lengths between the satellite and the IMRs, which are functions of the latitude and longitude of the IMR sites. Consequently, as well as providing the receiver with an amplified signal, IMRs also introduce a large amount of "artificial" multipath, with a larger number of signal components and wider delay spread than in T-UMTS. Notably, if the satellite link is not obstructed, the resulting multipath power delay profile (as shown in Fig. 2) consists of a direct line-of-sight (LOS) contribution due to the satellite link, and a number of mutually uncorrelated non line-of-sight (NLOS) strong IMR signal replicas. If there are enough fingers in the terminal RAKE receiver to collect them, an increased level of diversity is obtained. Otherwise, they result in additional system noise, with detrimental effects on receiver performance.

TERMINAL ARCHITECTURE

The minimization of terminal complexity is one key objective of this integrated architecture concept. Given that the terminal is satellite receive-only, significant savings are already achieved, since the power-demanding elements needed for uplink transmission toward the satellite are omitted.

Further trade-offs become relevant on the terminal side regarding its capability to access the services offered from the two radio networks simultaneously (e.g., receive MBMS from the satellite while interactively browsing the Web via the terrestrial network). The manner in which both services coexist has a direct impact on the required network-level integration and terminal configuration.

The *parallel* receiver architecture, implying additional *dedicated* hardware to support a satellite access scheme, would allow reception of services from both access networks at the same time. An extra radio frequency (RF) chain and baseband chip next to the T-UMTS chain ensure independent operation of satellite-related functions in the UE; the terminal is able to receive and/or transmit from/to the T-UMTS and receive from the S-UMTS radio access networks *concurrently*. Apparently, no significant reuse of receiver hardware is possible in this case.

The alternative is a reconfigurable receiver architecture capable of switching between terrestrial and satellite mode. For this terminal type *either* a bidirectional terrestrial link *or* a satellite unidirectional downlink is possible, meaning the user terminal does not support simultaneous delivery of both basic UMTS services and MBMS. In the ideal theoretical case, only one hardware chain is used at the terminal. However, a complete reconfigurable approach will be technically impossible, especially for the RF part. Some dedicated filters and power amplifiers will be necessary due to differences in the frequencies used for the two networks. A highly flexible architecture is required in this case, calling for satellite radio interface specifications as close as possible to the T-UMTS standard.

THE PROPOSED SATELLITE RADIO ACCESS SCHEME

UTRA FDD LAYER 2 AND 3 ADAPTATION

The UTRA layer 2 is functionally split into four sublayers: radio link control (RLC), medium access control (MAC), packet data convergence

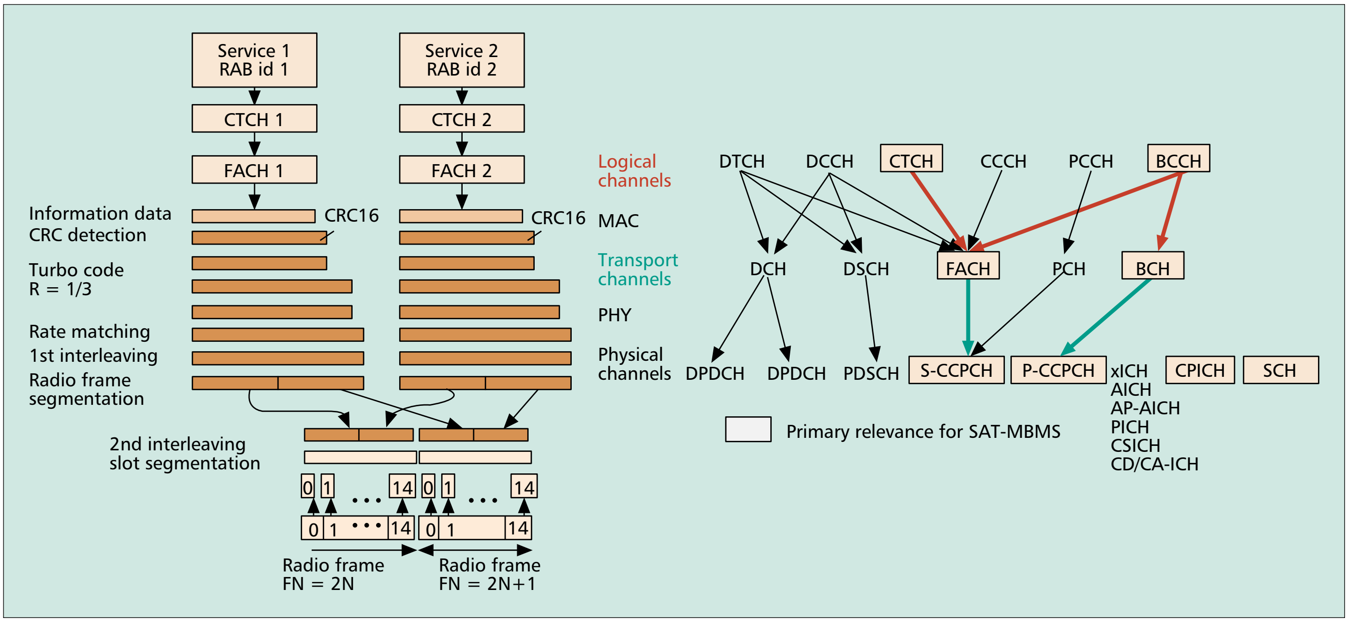

Figure 3. *UTRA FDD common logical/transport/physical channels retained in the interface and service mapping throughput the layers.*

protocol (PDCP), and broadcast/multicast control (BMC). The first two sublayers exist on both the data and control planes, whereas the last two exist only in the data plane. The data transfer services offered by the MAC to the RLC sublayer as well as the services provided by the physical layer to MAC vary and are grouped into specific sets abstracted into the terms *logical* and *transport channel*, respectively. The overall service provided by layer 2 is referred to as radio bearer (RB). Control plane signaling between UEs and UMTS terrestrial radio access network (UTRAN) is handled by the radio resource control (RRC) layer (UTRA layer 3).

The channels retained in the proposed interface at the data and control planes as well as the flow of data through UTRA layer 2 are depicted in Fig. 3. The main features of this interface are summarized below.

Channel and Mappings — The unidirectional nature of the system does not allow the setup and release of dedicated channels, which are not relevant anyway given the point-to-multipoint nature of the services under consideration. Multicast/broadcast services are mapped one-to-one on common traffic channels (CTCHs) at the RLC sublayer and forward access channels (FACHs) on the MAC sublayer, which are then multiplexed at physical layer on secondary common control physical channels (S-CCPCHs). The latter feature fixed spreading factors (SFs) and no power control. Given that in T-UMTS the FACH/S-CCPCH carries important signaling information, the standard practice is to allocate a small rate (respectively large SF) to it so that it can be accessible by all users in the cell. However, in the proposed integrated system S-CCPCHs are used mainly for data transfer purposes, so their SF can vary in the whole range defined in 3GPP standards (i.e. from 4 to 256). A separate S-CCPCH of low rate, called the *master S-CCPCH*, is reserved for signaling related to service notification.

Layer Functional Description — The access scheme sublayers support only a subset of the full functionality described in the 3GPP standards related to the retained common channels.

Multimedia data make use of the UMTS RLC *unacknowledged mode* over the satellite radio interface; the RLC sublayer provides basic sequencing and protocol maintenance functions without catering for error recovery functions such as automatic repeat request (ARQ).

The MAC sublayer is primarily responsible for scheduling different services over the air. Data are forwarded to the physical layer at certain time instants, which are spaced by transmission time intervals (TTIs) of 10/20/40/80 ms, according to the per-TTI selected transport format combination (TFC). The TFC defines how much data from which service flow should be forwarded to the physical layer and involves the prioritization of certain flows over the others.

The BMC sublayer is the one retained as the basis for the support of broadcast/multicast traffic in the forward link and the one that was subject to most modifications. The adopted approach is overall conservative in that it draws heavily on existing functionality related to the support of cell broadcast service (CBS), the unique service up to T-UMTS Release 5 that is delivered in point-to-multipoint mode over the UTRAN. Functions related to CBS data (storage, scheduling, power saving) are extended to MBMS data, and new features, such as messages and protocol entities, are added. The enhancements of BMC with respect to Release 5 T-UMTS BMC are summarized in Table 1.

The Radio Resource Control Layer — In the proposed interface, the functions of the RRC layer are again a subset of the full T-UMTS RRC functionality. Common traffic radio bearers of the cell/beam are established/maintained and released by the RRC peer entities. The RRC of the satellite RNC configures the

BMC feature	T-UMTS	Proposed interface	Comment
BMC entities	One per cell	One per MBMS service	In addition to the service-specific BMC entities, there are master BMC entities (one at S-RNC and one per terminal) responsible for overall notification information
Radio bearer	Single CTCH/FACH/S-CCPCH per cell	Multiple CTCHs/FACHs multiplexed over ≥ 1 S-CCPCHs	The maximum rate for T-UMTS CBS is 32 kb/s The maximum rate in the proposed system is 312 kb/s
Transport block (TB) size	Fixed	Variable	The use of variable TB size allows higher flexibility for the packet scheduling task
Messages	a) CBS data b) Schedule	The same two messages + two more: Notification message Notification change message	In T-UMTS, schedule messages are carried in-band (i.e., on the same CTCH/FACH carrying CBS data, and indicate the timing of a message within the CBS data stream. In the proposed system, service mappings are carried on the master S-CCPCH
Level 1 scheduling	Based on system information messages (BCH/P-CCPCH)	Based on notification and notification change messages (master CTCH/FACH/S-CCPCH)	Level 1 scheduling facilitates power-saving features at the terminal. In T-UMTS it provides the timing of CBS data on the single CBS S-CCPCH. In the proposed system, it provides the timing of different CTCH/FACHs on the data S-CCPCHs
Level 2 scheduling	Based on CBS dchedule messages — DRx on CTCH content	Relevant only for push and store services	Provides the timing of individual items (HTML pages, audio/video clips) within a given CTCH/FACH carrying push and store services

DRx: Discontinuous reception (data delivery mechanism implemented over the radio interface that allows mobile terminals to save power consumption during reception of CBS data)
BCH: Broadcast channel (transport channel)
P-CCPCH: Primary Common Control Physical CHannel

Table 1. *Enhanced CBS/MBMS in the proposed radio interface with respect to the T-UMTS Release 5 CBS.*

MBMS/CBS related channels and signals the availability of CBS and MBMS notification on the master S-CCPCH via unidirectional system information messages. These messages are received by UEs on the primary common control physical channel (P-CCPCH) and forwarded to the peer UE RRC entities. The latter configure the lower UE layers for data reception and forward the required information to physical layer for the implementation of power saving features (discontinuous reception, DRx).

UTRA FDD PHYSICAL LAYER ADAPTATION

The physical layer specifications provided in the 3GPP recommendations[2] have been analyzed and their applicability to the proposed architecture has been investigated so that modifications in the air interface are minimized.

On one hand, the provision of the return link via the T-UMTS network facilitates the adoption of WCDMA specifications. On the other hand, the propagation channels experienced in the forward link substantially differ from those used for T-UMTS design and evaluation. The propagation channel resulting from IMR introduction is modeled as a tapped delay line with fixed delays and amplitudes that follow Rice and Rayleigh distribution for the LOS and NLOS links, respectively. Furthermore, whereas the paths can be assumed mutually uncorrelated, the Doppler spread due to the terminal movement affects the time correlation of the fading process of each path.

Considering this scenario, a detailed performance analysis was carried out to verify that the desired quality of service (QoS) could be achieved with the given link budget adopting the physical channel structure and procedures enforced by 3GPP.

The WCDMA cell search procedure was analyzed from both the performance and complexity points of view. This procedure is continuously executed by the terminal, with the aim of acquiring time, code, frame, and base station synchronization. Results demonstrated its complete applicability to the system under consideration [4].

The achievable performance of S-CCPCH, the selected channel for the delivery of MBMS services, was assessed via extensive computer simulations under different propagation scenarios. Two examples of this assessment are reported in Fig. 4. Bit error rate (BER) and block error rate (BLER) are shown employing a spreading factor SF = 8 and turbo coding in two typical propagation scenarios: a Ricean satellite channel and the wideband channel generated by the IMR layout. Notably, the Ricean channel is representative of rural or suburban environments, where no IMR deployment is required and higher speeds (i.e., 200 km/h) are more likely, whereas the wideband channel deriving from IMR coverage is more likely in an urban scenario, where terminal speeds are limited (i.e., 50 km/h). In both cases the desired QoS, BLER = 10^{-3}, is achieved with E_b/N_0 values well below the available ones. Interestingly, these results show that the higher the data rates, the better the performance. This behavior is justified by the fact that for a given spreading factor, an increase in the data rate corresponds to an

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[2] *3GPP Technical Specifications 25.201, 25.211, 25.212, 25.213, 25.214, available at http://www.3gpp.org*

increase in the code block length and results in higher efficiency of the turbo code interleaver. This observation led to the design of the different strategies to map services onto physical channels, described in the next section. Taking into consideration these mapping strategies and different service scenarios [5], it has been shown that the proposed architecture can achieve aggregate bit rates (i.e., forward link capacity) larger than 1.4 Mb/s per single beam. These results motivated the direct adoption of the WCDMA physical layer for the forward link of the proposed system without any modifications.

The system performance can be further improved if nonstandardized coding and modulation techniques are adopted. In particular, *layered coding* techniques (serial concatenation of the UMTS convolutional encoder with a suitable inner encoder) offer the flexibility of trading off performance for complexity. For lightly loaded cases and good channel conditions the simple UMTS decoder suffices for most users to adequately receive the downlink MBMS signal. On the other hand, as the interference and channel conditions deteriorate, the much lower received E_b/N_0 dictates the use of a soft-input soft-output (SISO) decoder. Thus, the coverage efficiency of the system is maintained at the cost of extra decoding complexity for the majority of user terminals. The choice of a suitable layered coding structure is also a trade-off between performance, throughput, and complexity [6]. Finally, the use of high-order modulation schemes, 8-phase shift keying (PSK) and 16-quadrature amplitude modulation (QAM) can achieve up to double the capacity under ideal conditions but require the adoption of predistortion or equalization techniques to compensate for the nonlinear effects introduced by the onboard high-power amplifiers [5].

RADIO RESOURCE MANAGEMENT

The standard task of radio resource management (RRM) is to allocate physical radio resources when the RRC layer requests them. RRM aims to maximize spectral efficiency and satisfy QoS requirements, while preserving the radio resources of the network: available codes, bandwidth (spectrum), and transmit power. The main differences between the RRM tasks in the proposed interface and those in unicast T-UMTS stem mainly from the unidirectional nature of the system and the point-to-multipoint service topology.

System Implications — The absence of a satellite return link means that the satellite RAN cannot have real-time feedback from the usergroups (e.g., user-side measurements), directly restricting the system short-term RRM functions: no power control is feasible, and the packet scheduler decides on its allocations without knowledge of the state of individual channels (i.e., channel-state-dependent scheduling is not possible). In both cases, even if a return satellite link were available, the information feedback by the users would have to be exploited in an unconventional manner due to the point-to-multipoint nature of the services.

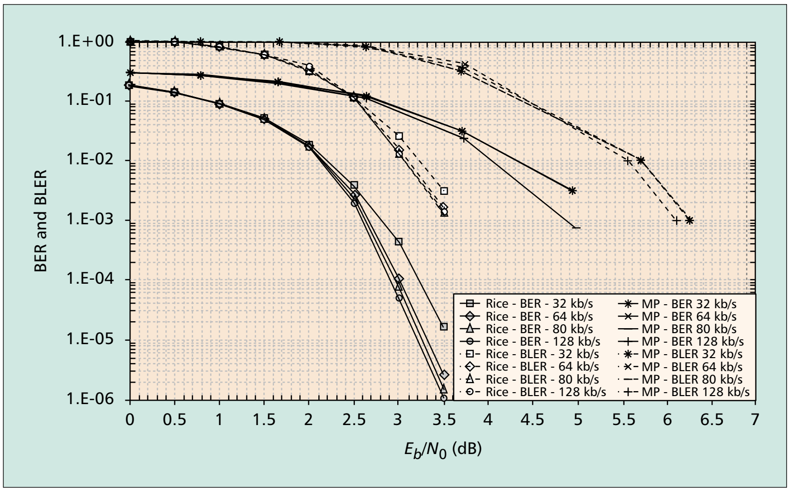


Figure 4. *BER and BLER in Ricean and combined satellite + IMRs channel (MP) for different rates (transport block sizes, respectively).*

Service Requirements — Additional requirements for RRM arise from the supported services and more generally from the overall service delivery paradigm. The satellite system can be envisaged as a content delivery network (CDN), primarily oriented toward *streaming* (e.g., audio, video broadcasting, alert and emergency announcements) and *push and store* applications (e.g., infotainment, entertainment, software delivery, Webcasting). In the first case the multimedia contents are played directly upon reception at the user terminal, whereas in the second the multimedia contents are stored in a local cache for later processing (*prestored content*). The RRM functions for each service type are somewhat different.

RADIO RESOURCE MANAGEMENT STRATEGY

The main RRM functions relevant to streaming services (partially real-time services) are admission control (AC), load control (LC), packet scheduling (PS), and the radio bearer allocation and mapping (RBAM) function. The latter is responsible for the RB configuration, that is, 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. Push and store services, on the other hand, are mainly handled by the broadcast dcheduler (BS). Two modes of operation are envisaged for the RRM of the proposed system.

In *RRM mode A* the RBAM dimensions the system and derives an RB configuration that remains fixed for some interval of time over which traffic exhibits stationary or semi-stationary behavior. The task makes use of traffic predictions, based on measurement data and user/group profile availability. The AC then functions within the additional constraints imposed by the RB configuration determined by RBAM.

In *RRM mode B*, on the other hand, the RB configuration is executed ad hoc by AC without any prior configuration. AC decides on the acceptance or rejection of a service request on the basis of power and load constraints, assuming infinite flexibility regarding the RB mapping and allocation: the RBAM will remap FACHs onto S-CCPCHs and reconfigure them, as far as a service request is accepted in terms of the extra load and power constraints it introduces. The second option allows higher flexibility in resource utilization [7] at the expense of extra interlayer and over-the-air signaling (reconfiguration messages toward group users that cannot be acknowledged by them).

The TFCS should be broad enough to capture the packet-level dynamics of the services expected over some future time interval. The wider the range of services, the broader the TFCS should be with direct impact on the terminal processing requirements.

RADIO BEARER ALLOCATION AND MAPPING

The RBAM block becomes more relevant in mode A, under which it dimensions the system for the streaming services portion of the traffic mix. Input to this task is the characterization of each service i in terms of mean arrival rate λ_i, mean service duration μ_i, and requested rate R_i. The task is executed separately for each satellite beam and evolves in three main steps.

Estimation of Required CTCH/FACHs — The RBAM first derives the expected traffic load per service on the basis of the service characterization, user group profile, and available information about the audience of each service. Let S be the set of different services and N its cardinality: $|S| = N$. Each element s_i corresponds to a member of the service set (i.e., a service). A service flow is characterized by the three-tuple $\{\lambda_i, \mu_i, R_i\}$; in this context, audio broadcast at 32 kb/s is regarded as a different service flow than audio broadcast at 64 kb/s. No assumption is made for the flow burstiness; the flow might be constant bit rate (CBR) or variable bit rate (VBR), but in the latter case the R_i value is set to the mean/guaranteed rate attribute. If P_{bl} is a vector of size N corresponding to blocking probabilities targeted for each service, with one-to-one correspondence between s_i and P_{bl}^i, the RBAM invokes well-known results of classical queuing theory — the multiserver loss (M/M/m/m) modes and their extensions for multiple services [8] — to estimate the required number of FACHs that can guarantee the target service blocking probability P_{bl}^i.

Mapping of FACHs on S-CCPCHs — The next RBAM task is the mapping of the derived FACHs onto the available S-CCPCHs. Link budget exercises and link-level simulation results provide estimates for the number of S-CCPCHs M that can be supported and their maximum capacity c.

There are two options for this mapping. The first ignores the power requirements (E_b/N_0) of individual services, attempting to minimize the required number of S-CCPCHs, while the second aims at a mapping that minimizes power usage (i.e., allocates services of similar power requirements to the same S-CCPCH, since services mapped on the same physical channel will eventually be transmitted with the same power).

Both alternatives can be formulated within the generic framework of bin packing problems; the requirement in both cases is to pack bins (FACHs) of size R_j into knapsacks of size c. The difference lies in the objective functions considered in each case [9]. Approximate algorithms (e.g., [10]) and their ad hoc adaptations suffice for the treatment of the first and second problems, respectively.

Derivation of TCFS for Each S-CCPCH — Strict rules or algorithms for performing this task are difficult to devise. In any case, deriving the TFCS a priori on the basis of traffic predictions is not too efficient. The TFCS should be broad enough to capture the packet-level dynamics of the services expected over some future time interval. The wider the range of services, the broader the TFCS should be with direct impact on the terminal processing requirements.

The chosen transport block (TB) sizes should be in line with the packet sizes expected from the applications so that framing overheads (headers and padding) are minimum. The same reasons (minimization overheads and resource utilization efficiency) dictate transport formats (TFs) for each FACH that can cover the full range of short-term rate variations.

ADMISSION AND PREVENTIVE LOAD CONTROL

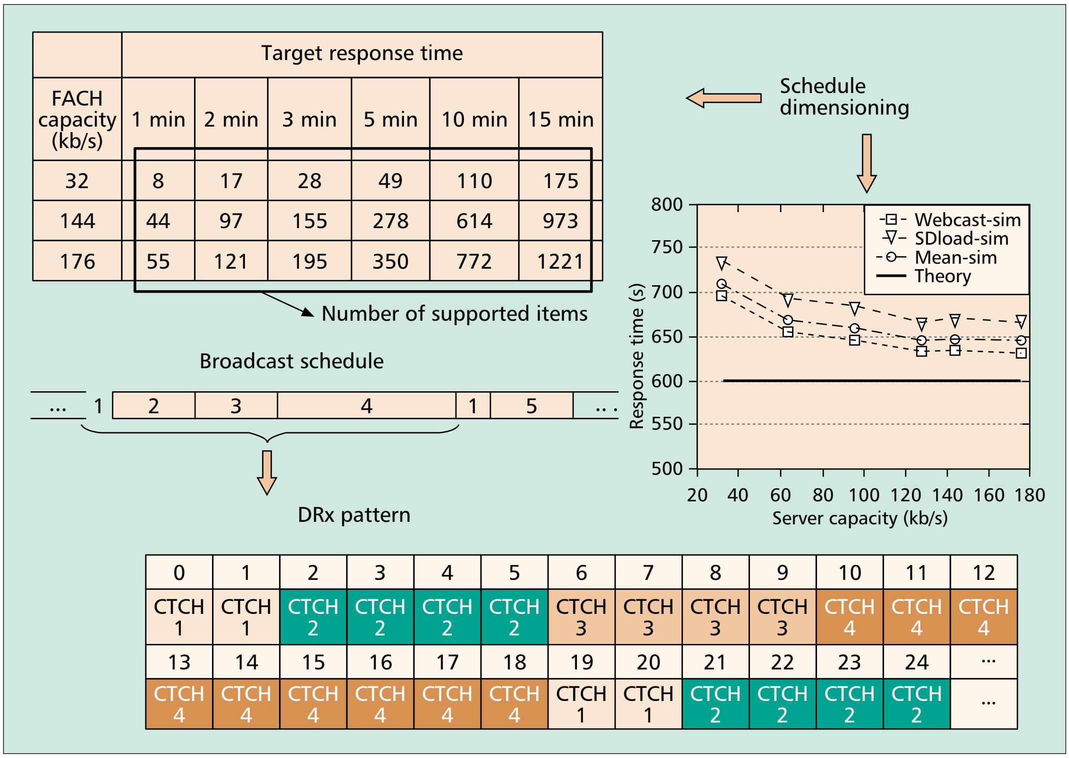
The admission control comprises the set of actions taken by the satellite network during the phase of service establishment or service re-negotiation to decide whether to accept or to reject a user group service request. A new user group service request can be accepted only when there are adequate network resources available to guarantee the QoS of all existing and the requested services. In the integrated system all user groups share the common bandwidth and each new user group that is established increases the interference level of all existing user groups, affecting their QoS. Moreover, given the particular system architecture the offered broadcast/multicast services require downlink only radio resources.

Load control, on the other hand, monitors, detects, and handles situations where the system approaches an overload situation while RBs remain active. Therefore, when somewhere in the network limited resources degrade service quality, load control brings the system back and restores stability seamlessly.

In the integrated system, admission control is coupled with a preventive load control mechanism. In fact, it is an admission control strategy that incorporates a preventive load control algorithm aimed at determining the admissible set of transport block set sizes (TBSs) that can be supported by the system, ensuring the required QoS. This combined strategy can be applied to cases where more than one FACH are multiplexed on a single S-CCPCH. The AC algorithm considers QoS, power, code, and per-SCCPCH rate constraints.

AC first checks the allowable TFCs by applying the QoS and power constraints. In the case of fixed mapping it then checks whether there are available FACHs with allowable information rate greater than the requested rate for the incoming service request. AC provides the allowable combinations from which the corresponding TFCS are derived (it is possible that the resulting TFCS is a reduced set following the application of additional constraints).

If the AC criteria are satisfied, preventive LC takes over and checks what would have been the total load for each transport format combination (TFC) available at the specific S-CCPCH if the new session were accepted. If this load criterion is also satisfied then the session is accepted and the



FACH capacity (kb/s)	Target response time 1 min	2 min	3 min	5 min	10 min	15 min
32	8	17	28	49	110	175
144	44	97	155	278	614	973
176	55	121	195	350	772	1221

0	1	2	3	4	5	6	7	8	9	10	11	12
CTCH 1	CTCH 1	CTCH 2	CTCH 2	CTCH 2	CTCH 2	CTCH 3	CTCH 3	CTCH 3	CTCH 3	CTCH 4	CTCH 4	CTCH 4
13	14	15	16	17	18	19	20	21	22	23	24	...
CTCH 4	CTCH 4	CTCH 4	CTCH 4	CTCH 4	CTCH 4	CTCH 1	CTCH 1	CTCH 2	CTCH 2	CTCH 2	CTCH 2	...

Figure 5. *Broadcast schedule dimensioning and discontinuous reception (DRx) implementation for push and store services.*

System capacity not required for streaming services is used for the delivery of push and store services. This is either the residual capacity after RBAM dimensioning in RRM mode A or prereserved capacity in RRM mode B, and is organized into FACHs carrying broadcast schedules.

selected TFCS is available to PS via RBAM. The above process reduces the probability of congestion depending on how conservative or optimistic the selection of the load threshold value is, and partially makes up for the inability of the unidirectional system to *react to* congestion events.

THE BROADCAST SCHEDULER

System capacity not required for streaming services is used for the delivery of push and store services. This is either the residual capacity after RBAM dimensioning in RRM mode A or prereserved capacity in RRM mode B and is organized into FACHs carrying *broadcast schedules*.

Each broadcast schedule carries several *items* of various content types such as compressed HTML pages, audio files, video clips, and software packages. The requirement for these services is the design of efficient broadcast schedules (cycles) that, in combination with cache management algorithms at the terminal side, minimize the average *response time*. This is defined as the time elapsing from the moment a user expresses his/her will to receive some content up to the moment the content is stored at his/her terminal, averaged over all items. Users express their will to receive content, for example, via selecting a choice at the terminal. The terminal then, knowing from the announcement channel (master CTCH/FACH) when the requested item is next transmitted and the respective configuration information, turns to the appropriate S-CCPCH, receives the item, and returns to the master-FACH reception state.

The design of optimum broadcast schedules has been the object of research since the times of teletext [11]. Algorithms such as those in [12] can serve this task. Inputs to these algorithms are the number and sizes of the individual items and their demand probabilities. The latter can be regarded as measures of the subscribers' interest in individual items or, equivalently, as a way to quantify the audience size for each service. The more popular a certain item, the more frequently it appears within the broadcast cycle over the air, the trade-off being among the achieved response times, the capacity allocated to the broadcast schedules, and the number of items the schedules accommodate.

Apparently the design of broadcast schedules targeting different response times is a way to support service differentiation for push and store services. The main requirement is to support two or three different levels of service (priorities) (e.g., high, medium, and low priority) related to:

- Service types: All items of one service type may be allocated a higher priority than all content coming under a different service type. This becomes relevant if some service types have stricter (in relative rather than absolute terms) timing requirements. For example, rich video/audio messages providing highlights (e.g., goals) from an ongoing football match may be prioritized over audio/video clips (Fig. 5).
- Items within a particular service type: All messages or Web pages do not have the same priority. Items are prioritized differently depending on their actual content.
- User groups: The same items may be provided with different priority to different user groups. This involves replication of the respective items over more than one data stream, each featuring different frequencies

The packet scheduler is the single short-term resource allocation function of the system. Since channel-state dependent scheduling is not feasible, the scheduler impact on the achieved system throughput is limited. Nevertheless, the role of the scheduler remains important in satisfying the QoS requirements of multiplexed services.

of appearance for the items under consideration.

All three priority contexts — and any derivative combination — can be linked to charging considerations.

Moreover, estimates of the response time can be used for some type of admission/load control. A new item will be incorporated in the schedule, either as an additional one or after preempting a less popular item, as long as it does not push the response time beyond a predefined target value.

PACKET SCHEDULER

The packet scheduler is the single short-term resource allocation function of the system. Since channel-state-dependent scheduling is not feasible, the scheduler's impact on the achieved system throughput is limited. Nevertheless, the role of the scheduler remains important in satisfying the QoS requirements of multiplexed services. It consists of two main tasks.

Time Scheduling — It must time-multiplex 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, broadcast schedules carrying push and store services only require the provision of a constant long-term mean rate that will preserve the target average response time.

The scheduler is configured with a certain TFCS for each S-CCPCH, consisting of a number of transport format combinations (TFCs). Each TFC comprises as many transport block set sizes (TBSs) as the number of FACHs mapped to the respective code channel. Each TBS defines how many bits from the respective FACH are forwarded to layer 1. The sum of all TBSs, corresponding to a single TFC, is upper-limited by the maximum allowed data rate of the code channel. The task of the scheduler is to select every TTI and for each S-CCPCH some *appropriate* TFC. The actual context of the term appropriate is dictated by several factors such as the service QoS requirements and the physical channel utilization efficiency, and differentiates one scheduler from another. In [13] two possible schemes, adaptations of well-known scheduling algorithms that have been used for years in the context of wired networks, are described and evaluated.

Power Allocation — The second task of the scheduler consists of adjusting the transmit powers of the code channels. Criteria for this allocation may be the packet/transport block size to be served (see the section on physical layer adaptation) or knowledge of the expected audience distribution within the beam. This power adjustment is not, therefore, of the same granularity as the conventional fast power control mechanism, but rather limited to a small set of values. The scheduler trades transmit power against coverage and user reception quality.

CONCLUSIONS

The inherent broadcast capabilities of satellites render them an attractive solution for the delivery of multicast and broadcast services. The close cooperation with terrestrial mobile networks bears benefits for both mobile and satellite operators. The adoption of the same interface in the satellite radio network significantly reduces terminal complexity, providing the user with additional capabilities at minimum cost.

This article has proposed a satellite radio access scheme that fulfills this objective. Having as a starting point the WCDMA interface of T-UMTS, we have outlined the individual layers of the access scheme and the respective RRM strategy. Its adaptation to the satellite case consists mainly of simplifications and, to a lesser extent, modifications of the interface layers, taking into consideration the particular requirements that stem from the point-to-multipoint service topology and unidirectional system nature. We have described the main trade-offs related to this access scheme, providing links to papers where their detailed evaluation was carried out.

This original architecture is now being standardized within the European Telecommunications Standard Institution (ETSI) S-UMTS Working Group and is also under investigation by other projects funded by the European Union and European Space Agency (ESA), such as the EU projects Mobile Digital Broadcasting Satellite (MODIS) and Mobile Applications and Services based on Satellite and Terrestrial Interworking (MAESTRO), which aim to show its technical and economical feasibility through field tests and demonstrations. Furthermore, within these projects the feasibility of a direct return link through satellite is under investigation to allow the deployment of infrastructure that can respond to public protection and crisis management requirements.

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REFERENCES

[1] 3GPP TS 23.246, "Multimedia Broadcast/Multicast Service (MBMS): Architecture and Functional Description," Rel. 6, Dec. 2003.

[2] P. I. Philippopoulos, N. Panagiotarakis, and A. Vanelli-Coralli, "The Role of S-UMTS in Future 3G Markets," *Business Briefing, Wireless Tech. 2003*, World Markets Rese. Ctr. Ltd. (http://www.wmrc.com), Jan. 2003.

[3] T. Severijns *et al.*, "The Intermediate Module Concept within the SATIN Proposal for the S-UMTS Air Interface," *IST Mobile Summit 2002*, Greece.

[4] C. Caini *et al.*, "Initial Synchronization Procedure in S-UMTS Networks for Multimedia Broadcast Multicast Services," *IEEE PIMRC 2002*, Lisbon, Portugal, Sept. 15–18, 2002, pp. 295–99.

[5] K. Narenthiran *et al.*, "S-UMTS Access Network for Broadcast and Multicast Delivery: The SATIN Approach," *Int'l. J. Satellite Commun. and Net.*, Jan.–Feb. 2004

[6] A. Levissianos *et al.*, "Layered Coding for Satellite and Terrestrial Multipath Correlated Fading Channels," *1st Int'l. Conf. Adv. Mobile Satellite Sys.*, Rome, Italy, July 2003.

[7] E. Angelou *et al.*, "Admission and Preventive Load Control for Delivery of Multicast and Broadcast Services via S-UMTS," *1st Int'l. Conf. Adv. Satellite Mobile Sys.*, Frascati, Italy, July 2003.

[8] J. Kaufman, "Blocking in a Shared Resource Environment," *IEEE Trans. Commun.*, vol. 29, no. 10, Oct. 1981, pp. 1474–81.

[9] M. Karaliopoulos *et al.*, "Radio Resource Management Strategy in SATIN," *12th IST Mobile & Wireless Commun. Summit*, Aveiro, Portugal, June 2003.

[10] S. Martelo and P. Toth, *Knapsack Problems: Algorithms and Computer Implementations*, Wiley, 1990.

[11] M. H. Ammar and J. W. Wong, "The Design of Teletext Broadcast Cycles," *Perf. Eval.*, vol. 5, no. 4, Dec. 1985, pp. 235–42.

[12] N. Vaidya and S. Hameed, "Scheduling Data Broadcast in Asymmetric Communication Environments," *Wireless Networks*, vol. 5, no. 3, May 199, pp. 171–82.

[13] M. Karaliopoulos *et al.*, "Packet Scheduling for the Delivery of Multicast/Broadcast Services via S-UMTS," *Int'l. J. Satellite Commun. and Net.*, Sept.–Oct. 2004.

BIOGRAPHIES

MERKOURIS KARALIOPOULOS (M.Karaliopoulos@ieee.org) was awarded his Diploma in electrical and computer engineering degree from the Aristotle University of Thessaloniki, Greece, in 1998 and a PhD degree in broadband satellite networking from the University of Surrey, United Kingdom, in 2004. Since 2002 he has been a research associate at the Center for Communication Systems Research of the University of Surrey, working on EU projects in the area of mobile satellite communications systems and participating in other European actions in the area of satellite networking such as COST action 272 and the European Satellite Network of Excellence (SatNEx). His main research interests are in the area of mobile and wireless data networking, with emphasis on radio resource management, multiple access, and transport protocols.

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The inherent broadcast capabilities of satellites render them an attractive solution for the delivery of multicast and broadcast services. Close co-operation with the terrestrial mobile networks bears benefits for both the mobile and the satellite operator.