An Advanced Satellite UMTS Testbed for Laboratory and Over-the-Air Experiments of Third-Generation Mobile Services: Part I—System Design Aspects

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Abstract—This paper provides an overview of the advanced S-UMTS testbed (ATB; S-UMTS = satellite universal mobile telecommunication system) project that is funded by the European Space Agency, which is instrumental to define, validate, and demonstrate the adaptations of third-generation (3G) mobile technologies based on wideband code-division multiple access (W-CDMA) for supporting via-satellite services. Such services are often generically referred to as S-UMTS. One of the main project targets was to develop and demonstrate, in the laboratory and over the air, a set of technical solutions for the efficient provision of point-to-point (PTP, i.e., interactive) and point-to-multipoint (PTM, i.e., multicasting/broadcasting) services to best exploit the precious satellite communications resources. With respect to previous work, which was mostly devoted to the connection-oriented mode (i.e., circuit basis), particular emphasis was dedicated to optimizing solutions for the connectionless modes (i.e., packet basis and reliable multicasting/broadcasting, both real time and nonreal time). As a matter of fact, the wide-area delivery of multimedia services to mobile users is expected to represent the most important commercial opportunity for S-UMTS systems, as witnessed by recent initiatives taking place in the United States, Korea, and Japan. After dwelling on the aims of the ATB project, this paper presents the key required adaptations and extensions, for satellite applications, to the W-CDMA scheme as standardized by the Third Generation Partnership Project for terrestrial applications. This paper then continues by describing the architecture of the real-time end-to-end testbed (taking the name ATB after the project name), which was developed with the main objective of supporting laboratory and over-the-air trials, and its main constituting elements. In a companion paper, the architecture of the overall via-satellite demonstrator, which is largely based on the ATB, is addressed, together with the key results of the laboratory and over-the-air trials.

Index Terms—Mobile communications, satellite mobile communications.

I. INTRODUCTION

MOBILE satellite communications, which originally started in the 1970s with the Marisat and Inmarsat systems, saw strong growth in the 1990s when the so-called satellite personal mobile communication networks (S-PCNs) were conceived and subsequently deployed. Whereas Iridium preferred to adopt a proprietary approach, Globalstar, Thuraya, and Aces pursued the adaptation of second-generation (2G) cellular air interfaces [global system for mobile communications time-division multiple access (GSM TDMA) or IS-95 code-division multiple access (CDMA)] to the satellite context. Generally speaking, S-PCNs provide 2G services (e.g., voice, fax, and low-rate data) to handheld mobile terminals (MTs), thus coping with most of the requirements users had at that time. In the meantime, the mobile operators, pushed by the 2G networks bandwidth constraints that cause such networks to be hardly suitable for high-speed applications, started to plan the deployment of new third-generation (3G) cellular networks meeting the needs of customers requiring high-speed services, with the target of introducing them by the beginning of the forthcoming new century on a global basis. The major objectives of the new system intended to support the 3G services, called the universal mobile telecommunication system (UMTS) or the International Mobile Telecommunications 2000 (IMT-2000), were set forth by the European Telecommunications Standards Institute (ETSI) and the International Telecommunication Union (ITU) as follows: 1) a wide service offer, encompassing multimedia; 2) integration of different service types, either consumer or business, into a single cellular network; 3) all services can be enjoyed using a single MT type; 4) a unique worldwide dialing number, independent of networks and service providers; 5) overall capacity that is high enough to serve more than 50% of the world population; and 6) integration of different components, including the via-satellite one, into a single framework.

Along such an evolutionary path, the European Space Agency (ESA) has been promoting investigations and demonstrations of advanced wideband techniques, permitting satellite systems to keep pace with the dynamic world of mobile cellular networks. Such techniques led to the satellite UMTS (S-UMTS) vision as a component of the overall mobile network that will permit to achieve a seamless coverage, on a global scale, while maintaining MT compatibility and service portability. More
specifically, the major S-UMTS objectives are 1) to permit worldwide roaming to the UMTS users, 2) to feature a service quality that is comparable with that of the terrestrial component at an affordable cost, and 3) to foster the deployment of UMTS services over large geographical regions, including the developing countries, in a quick and cost-effective manner.

The ESA strategic approach with regard to the S-UMTS, defined with the aid of in-depth technical investigations, was to adopt transmission techniques, called satellite wideband CDMA (SW-CDMA), that represent an adaptation of the emerging terrestrial standards based on the Third Generation Partnership Project (3GPP) W-CDMA technology, rather than developing a satellite-specific air interface \textit{ex nvo}. The terrestrial and satellite techniques were kept as close as possible, wanting to maintain a high commonality extent and to pursue an open standard approach as much as possible, with the aim of enjoying a high economy of scale yielding a favorable impact on dual-mode (i.e., terrestrial/satellite) MT cost. Such an approach was supported by several key players not only in Europe [20].

The first initiative that the ESA undertook in that perspective was the launch of the so-called Robust Modulation and Coding for Personal Satellite Communications Systems (ROBMOD), which had the main objective of defining in detail [3] and implementing a robust SW-CDMA physical layer, offering customers good-quality circuit-switched services. The study and simulation activities performed within that project were pivotal for the ESA submission to the ITU in 1998 of two Radio Transmission Technology proposals, namely, SW-CDMA and satellite wideband code–time division multiple access (SW-CTDMA), the latter being a time-duplexing version of the proposed technique. Both proposals were accepted by the ITU [1] and are now part of the ITU IMT-2000 standards family. Moreover, in 1999, the ESA prepared four technical specifications for the S-UMTS “family A,” which were approved by the ETSI in 2000 [2]. The initial ROBMOD study and simulation activities were complemented by the implementation of a laboratory testbed (called the ROBMOD testbed (RTB) [4]), which is a comprehensive hardware-based testing facility that is representative of the S-UMTS physical layer, supporting circuit-switched services over the SW-CDMA standard.

The follow-on project, called the advanced S-UMTS testbed (ATB), was deployed with the main objective of realizing an even more versatile S-UMTS test platform, which still today constitutes a rather unique facility with regard to S-UMTS validation. The capabilities of the new testbed (taking the name ATB after the project name) are, by far, greater than those of previous developments (e.g., Satellite Integration into Networks for UMTS Services (SINUS) [14]—a predecessor R&D project funded by the European Commission). In addition to the legacy RTB functions and physical-layer capabilities, the ATB supports new operational modes (mainly packet and reliable multicast) by means of augmented physical-layer capabilities and newly defined upper layer protocols. For the downlink, the shared packet channel solution specified by 3GPP–Release 5 has been retained with some modifications aiming to reduce the signaling overhead. For the uplink (UL), due to the large satellite propagation delay, packet-mode solutions had to be customized for via-satellite operations as the corresponding 3GPP solutions were either nonapplicable or scarcely efficient. For reliable multicasting, an ad hoc layer-3 scheme was defined, exploiting a carouselling technique combined with a forward error correcting (FEC) scheme operating at a layer above the physical one. A Reed–Solomon (RS) encoding/interleaving (in large blocks) was selected; it allows one to significantly mitigate the impact of link interruptions or deep shadowing. In the ATB project context, an ad hoc IP-based application was also developed, which was designed to represent a good example of the service potentialities offered by satellite systems (with particular regard to location-based services).

The key ATB features are as follows: largely programmable real-time emulation of the complete [forward link (FL) and reverse link (RL)] mobile satellite communication system inclusive of a gateway (GW) station; support of two experimental MTs; true CDMA cochannel and adjacent channel interference; very realistic mobile channel simulators for low earth orbiting (LEO)/medium earth orbiting (MEO)/geostationary (GEO) constellations; connection oriented (voice over IP, videoconference); packet with different QoS and reliable multicast services; IP applications (Internet access, e-mail, streaming, file transfer, file push, etc.); support of laboratory and via-satellite configurations; and ad hoc application development for location-based services demonstration. The ATB SW-CDMA modems support satellite path diversity, multistep power control, CDMA interference mitigation at the user terminal (UT), and burst demodulation capabilities.

II. W-CDMA SATELLITE ADAPTATIONS FOR PACKET AND MULTICAST M0DES

The satellite mobile channel is quite different from the terrestrial one and requires adaptation of physical and medium-access control (MAC) layers to efficiently cope with it. In fact, the terrestrial UMTS channel is typically affected by lognormal long-term shadowing and Rayleigh short-term multipath fading, with generally no line-of-sight (LOS) component, except possibly in picocellular environments. In these conditions, the adoption of a rake receiver is certainly advisable to detect and combine the strongest multipath components and to allow for soft handoff. Multipath diversity provides increased QoS through fading mitigation. Conversely, due to the larger free space loss and onboard RF power scarcity, mobile satellite systems are forced to operate under LOS propagation conditions at least for medium-to-high data rates. This results in a milder Rice (or at most Rice lognormal) fading channel [20], with a Rice factor (the power ratio between the LOS component and the diffuse component) typically ranging between 7 and 15 dB. Multipath diversity in a single satellite link cannot be exploited due to the fact that paths with differential delays exceeding 200 ns most often result to have insufficient power to be usefully combined by the rake receiver. Thus, fading is effectively nonselective. Another major difference is that the \textit{useful} dynamic range for the received signal power is much smaller than for terrestrial systems (for which it goes up to 80 dB). This is due to the different system geometry (reduced path loss variation within each satellite beam, in the order of 3--5 dB) and, again, to the
limited onboard RF power, which is insufficient to counteract path blockage. Path blockage can be induced by heavy shadowing from hills, trees, bridges, and buildings; the car’s body and the head of the user can also have a nonnegligible impact. Tree shadowing can lead to 10–20 dB of excess attenuation and is often the cause of link outage. In essence, if the S-UMTS operates in an on/off propagation channel, with Rice fading in the on condition [20]. Countermeasures to blockage-induced outage are essential to achieve satisfactory QoS. Furthermore, propagation delay is also much larger than terrestrial networks, ranging from a few tenths of milliseconds in the case of LEO satellites to a few hundreds of milliseconds, which is typical of GEO satellites.

In the following, terrestrial W-CDMA adaptations at physical and MAC-layer levels are described for the packet and multicast modes to cope with the satellite channel characteristics. It is assumed that the reader is familiar with the satellite-specific adaptations that are required for the W-CDMA connection-oriented mode (3GPP R99) detailed in [3].

A. Unicast Packet-Mode Design

The ATB unicast packet-mode design was inspired to solutions emerging, at that time, from the W-CDMA frequency division duplex mode standardization (3GPP). Accordingly, the FL downlink shared channel (DSCH), which was already specified in 3GPP Release 99, was adapted to the satellite environment. With regard to the RL, an adaptation of the common packet channel (CPCH) that is specified by 3GPP Release 99 was first investigated, which came to the conclusion that any adaptation to the GEO satellite environment would suffer efficiency problems due to the satellite links delay. Other solutions were then investigated, namely, a spread-Aloha-based access, referred in the following as random access spread Aloha (RASA), which extends the random access channel (RACH) approach specified by 3GPP Release 99, and a reservation scheme referred to as dynamic rate on demand (dRoD). Both solutions have been retained, them being complementary to each other; as a matter of fact, the RASA approach was shown to produce a lower delay under light-to-moderate traffic load, whereas dRoD performs better under heavy load conditions. In this paper, it is only possible to show a subset of the great number of results produced during the ATB studies and simulations.

1) FL Access: The FL access adaptation was driven by the wish to eliminate the use of a data channel (DCH) that is associated to the DSCH. According to the 3GPP specs, only the dedicated physical control channel (DPCCH), part of the physical DCH, needs to be continuously transmitted for supporting closed-loop power control on the DSCH. Such DCH usage would nonetheless represent, in a satellite environment, a significant power waste and a bottleneck bound to the channelization codes shortage caused by the need to associate a DCH to each MT operating on the DSCH. In the terrestrial case, the DCH is released when the MT has been idle for a certain period, with a timeout that is short enough to limit the number of simultaneously active DCHs that are associated with the DSCH. However, in the satellite case, particularly for the case of GEO, a longer timeout should be used to avoid the packet delay caused by having to set up again a released DCH channel. These considerations suggested investigating alternative DSCH modes, not relying on associated DCHs for power control and signaling. In particular, two alternatives were investigated, i.e., one that is compatible with the closed-loop power control, and one that requires a different power-control strategy, here termed the “open-loop” power control. The latter one, which was preferred in the end, envisages the use of the shared signaling channel (SSCH), a channel that is utilized for carrying signaling information that is related to DSCH capacity assignment to MTs. Open-loop power control operates on a signal-to-noise plus interference ratio (SNIR), as measured by the MTs [on the common pilot channel (CPICH)]. When the MT is active, such measurements can be fairly frequently transmitted (e.g., 1 s), whereas their rate can be decreased after the inactivity timeout has expired.

The CPICH SNIR measurement quality in terms of accuracy and bias is enhanced by the availability, on such carrier, of unmodulated symbols. However, a bias may, anyway, result in setting the DSCH (and SSCH) power. Moreover, the target SNIR, offering the MT the requested QoS, may only be approximately determined, the current MT propagation conditions being unknown. All such factors lead to propose complementing such “inner” control scheme with an “outer” control loop [3], according to which the target MT SNIR used by the GW for calculating the required power is adjusted depending on whether the previous transmission by the GW was successful or not [13]. The so-adapted DSCH scheme would take advantage, for optimal performance, of satellite diversity should more than a single satellite be available (e.g., a LEO constellation). At this regard, either the conventional satellite diversity, i.e., maximal ratio combining (MRC), or a fast satellite selection mechanism could be used, or they could be even simultaneously used. By the latter approach, the GW selects the satellites to be used for actual transmission of the DSCH within the current active satellites set (known by the active set handling signaling) based on the latest available information on link quality. Such a mechanism is similar to the fast cell selection, which was proposed, in the terrestrial case, to enhance the 3GPP DSCH operation with the support of an (optional) advanced form of FL power control for macrodiversity environments called the site selection diversity transmission (SSDT). In the satellite case, differently from the SSDT, no ad hoc signaling is required to select the best satellite path, as the GW can determine it by monitoring the corresponding RL satellite paths quality. In fact, although RL and FL multipath fading are not correlated, the reverse is true for the case of shadowing and obstructions. Fig. 1 shows the performance of the DSCH with open-loop power control in an open environment with fading for the system parameters illustrated in Table I. Efficiency is normalized to the chip rate $R_c = 3.84 \text{ Mbit/s}$; hence, an efficiency of 100% would correspond to a throughput of 3.84 Mbit/s.

The DSCH may be actually heavily loaded, at least 70%, before delay rapidly increases. It appears that the main differences with the no-fading case reside in the increased transmission delay (mean and standard deviation) under low-load conditions. Under high-load conditions, the influence of fading is masked by the delay caused by congestion.
Fig. 1. Performance of DSCH with open-loop power control (MT SNIR estimation error standard deviation 0.5 dB; power-control bias variance 2 dB). Open environment with MT speed is equal to 3 m/s.

The assumed MT speed was 3 m/s. Simulations have been repeated for 70 km/h, and it appears that the achievable throughput is not significantly dependent on the MT speed. However, there is quite a significant impact on the average packet delay, notwithstanding the fact that the scheduler is not favoring the MTs in good propagation conditions. Similar consideration on packet delay can be also done with regard to the suburban environment results [13], where some further worsening of the delay performances has been observed. Simulations were done for a GEO satellite with an effective isotropic radiated power (EIRP) of 47.5 dB·W at the beam center. The maximum satellite RF power allocated to the DSCH channel was 1 W. Simulation results showed that the available RF power is not fully used even in high-load conditions, whereas the average power was always below −1 dB·W. Simulations done assuming a reading time of 10 s showed that more than 300 MTs can simultaneously have a packet session open. This implies that, if a DCH had been allocated to each MT, as in 3GPP, an excessive overhead would have resulted, thus implicitly confirming the validity of the proposed approach.

2) RL Access: As mentioned before, the 3GPP CPCH approach does not lend itself very well to applications in a GEO environment due the high round-trip delay. A detailed discussion of CPCH limitations in a GEO environment is given in [13]. The studies concluded that a classical reservation scheme for packet transmission dubbed dRoD could operate in combination with RASA [11], [15], with the aim to maximize channel usage as well as minimize channel delay. A strategy for selecting either of the two channel access mechanisms was implemented at the MT. Such a strategy is based on traffic volume. Below a certain volume, MT packets are transmitted using RASA, whereas at higher loads, the system reverts to dRoD-only access. The RASA/dRoD discriminating threshold is, however, decided at a network level and is broadcast by the GW to all MTs.

System simulations of dRoD and combined dRoD/RASA access schemes were performed (see Table I for simulation parameters).

Some simulation results are shown in Fig. 2 for a Poisson type of traffic. It should be remarked as the delay flatness versus the channel load of the RASA random access protocol. Differently from the (slotted) Aloha showing a quite steep delay increase with channel load, the RASA delay flatness is kept up to the peak of the throughput. This important feature that is particularly useful in satellite systems, where packet retransmissions shall be avoided, is due to the RASA low packet loss probability also for high-loaded conditions [15].

As stated before, the selection between dRoD and RASA is based on the current MT queue size. The GW broadcasts the RASA/dRoD decision threshold that is determined upon current system load. Every second, the GW also broadcasts all MTs, with the measured system load (noise rise) averaged over that interval. Moreover, the GW transmits to each MT requesting a bandwidth allocation the SNIR measured on the request (in addition to the allocation itself). That information can be used by the MT to calibrate the open-loop power control scheme. The power-control strategy on the RL is similar to that on the FL, i.e., open loop with measurements on the CPICH. However, in the RL, an estimate of the UL attenuation is actually required instead of the CPICH SNIR, which would not be appropriate, since it does not take into account the orthogonal interference contribution. Assuming similar UL and downlink attenuation, the CPICH measured level is used to estimate the downlink (and, hence, the UL) attenuation. We have not considered the possibility to track multipath fading, which is too fast compared with GEO satellite delay, and we have instead considered tracking the longer term fading. High calibration errors may, however, occur in CPICH level measurements at the MT. This bias (4 dB in the simulation of Fig. 2) is compensated for by the presence of an outer

<table>
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<tr>
<th>Traffic Model</th>
<th>ETSI Web Server (10 s read time)</th>
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<tr>
<td>MT peak EIRP</td>
<td>15 dBW</td>
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<tr>
<td>MS speed</td>
<td>70 Km/h</td>
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<tr>
<td>Number of simulated satellite beams</td>
<td>1</td>
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<tr>
<td>Satellite Beam Peak Gain</td>
<td>42.7 dBi</td>
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<td>Satellite G/T (coverage centre)</td>
<td>15.7 dB/K</td>
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<td>Coverage Area (beam width)</td>
<td>1 deg @ -2 dB</td>
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power-control loop as the one considered for the FL. The maximum GW noise rise value $NR_{\text{max}}$ parameter is lower in the fading case ($NR_{\text{max}} = 4$), as compared to the one assumed in the case without fading ($NR_{\text{max}} = 10$). The reason for using such a lower value for the $NR_{\text{max}}$ parameter lies in the fact that the assumed MT maximum EIRP (15 dB in the case without fading) is considerably lower than the maximum allowed by the regulations. This would lead to a service interruption during the shadowed state and, consequently, to a large average delay. Obviously, having reduced the maximum acceptable interference, the achieved maximum throughputs is somewhat reduced with respect to the case without shadowing. Simulation results for suburban environment show similar results.

B. Multicast Mode Design

Transmitting, in a reliable and efficient manner, the multicast traffic from the satellite to a great number of MTs is particularly challenging. In a GEO satellite environment, a great number of subscribers of multicast broadcast multimedia services (MBMSs) should be expected. Applying regular automatic-repeat-request (ARQ) schemes on individual PTP radio bearers for each MT would not be convenient due to poor efficiency in radio resources usage or could not be possible due to lack of an RL channel (RLC). The same applies to using an ARQ scheme on a single PTM radio bearer, which would not be applicable in the case of a great number of subscribers due to the resulting intolerably high number of retransmissions. As an alternative to ARQ, a novel FEC scheme with interleaving derived from the Digital Video Broadcasting-Handheld multiprotocol encapsulation FEC [23] has been developed and implemented in the ATB upper layers. The said concept combines FEC and interleaving in an ideal manner so that the interleaving/deinterleaving delays that are typically associated with a regular interleaving scheme can be reduced.

In the hybrid FEC/interleaving scheme, redundancy data are generated by applying RS encoding. Other systematic slightly suboptimum block codes, such as Raptor codes [19] featuring a more efficient decoding, would be also applicable in alternative to the proposed scheme.

Noticeably, user data are transmitted to the receiving peers over the forward access channel (FACH) in “plain text,” i.e., without interleaving the data itself. Instead, a copy of the data is locally maintained at the transmitter and temporarily stored in an interleaving matrix (i.e., FEC block).

Once such a matrix is filled up (or after a timer has expired), RS encoding is performed, using the stored data, to generate a block of redundancy data. Such redundancy data are then also sent to the receiving peers, after which the current interleaving matrix is flushed and filled with copies of new user-plane data. Interleaving is introduced in such scheme by performing RS encoding across several rows of user data when generating the redundancy data. In this way, each codeword is composed by taking user-data symbols that were actually spaced in time by $L$ symbols when they were transmitted ($L$ being the chosen interleaving size and row length of the interleaving matrix).

Fig. 3 illustrates this concept. Applying this concept, the interleaving delay is significantly reduced since user data do not need to be accumulated in an interleaving matrix for interleaving before they are sent to the receiving peers.

The only forwarding delay that is experienced by user data at the transmitter stems from the transmission of the redundancy data. Also, the deinterleaving delay can be reduced. Due to the “plain text” transmission of user data, as long as the data are correctly received at the receiving peer, they can be immediately forwarded to the higher layers. For such data, no decoding/deinterleaving is actually performed, as it would be required to first receive all data belonging to an interleaving matrix, as in the case of a regular FEC/interleaving scheme. Decoding (and, hence, implicitly also deinterleaving) is only required in case some data are missing or erroneous. In such an event, data forwarding to higher layers cannot take place until the currently missing data are reconstructed. Depending on the amount of data already received from the current FEC block, additional data must be received to reconstruct the erroneous data. Obviously, this results in some delay variations at the receiving peer. However, pure data-transfer MBMS services can easily accommodate such delay variations. For more jitter-sensitive services, a jitter buffer might be employed.

Furthermore, the “transparent” or “plain text” transmission of user data introduces another advantage: for MBMS services, data delivery in two different cells is typically not synchronized at the UMTS satellite radio access network. Nevertheless, a user might move from one cell to another within the same MBMS service area, hence not receiving all data belonging to the same FEC block. In the case of a regular FEC/interleaving scheme, any data received in the old cell cannot be typically deinterleaved/decoded with success due to the absence of data and must then be discarded. Furthermore, the start of a new FEC block must be awaited in the newly entered cell before data reception can continue. Through the “transparent” transmission of user data in the proposed combined FEC/interleaving scheme, any data received with success in the old as well as the same FEC block. In the case of a regular FEC/interleaving scheme, any data received in the old cell cannot be typically deinterleaved/decoded with success due to the absence of data and must then be discarded. Furthermore, the start of a new FEC block must be awaited in the newly entered cell before data reception can continue. Through the “transparent” transmission of user data in the proposed combined FEC/interleaving scheme, any data received with success in the old as well as the new cell can be still passed along to higher layers.

The strength of the proposed RLC scheme for multicast services is to ensure the integrity of the transmitted data while substantially reducing the interleaving delay and minimizing the deinterleaving delay, as compared to a traditional interleaving scheme. Further advantages are achieved thanks to the “transparent” transmission of user data.

To give a flavor of the UL FEC capabilities, few simulation results are reported for the two-state satellite channel Lutz model [21]. To simplify the UL FEC simulation, it is assumed that when the channel is in a bad state, then the received FEC codewords are in error. On the other hand, when the channel is in a good state, codewords are correctly received. An RS (175, 255) UL FEC code has been selected with a code rate of 0.686 and a block size variable from $10^2$ to $10^5$ codewords. First, an urban channel has been considered, and the corresponding simulation results are shown in Fig. 4.

As expected, the codeword error probability (CEP) decreases for increasing FEC interleaver block size and satellite elevation angle. It is noticeable that for small interleavers, the CEP is the same for both mobile speeds. This is an expected behavior,
as the average amount of time in an outage is the same for both speeds; therefore, the average CEP is the same. When the interleaver size is increased, the errors decrease more rapidly for the higher mobile speed, as, in this case, the outages are shorter, and a smaller interleaver is required to spread the errors for correction by the UL FEC decoder.

For FEC interleaver size (in codewords) of $10^4$ and greater, the errors are totally corrected for the 70-km/h case but not for the 3-km/h case. Increasing the satellite elevation angle improves performance, as the percentage of time in which the channel state is “on” increases, thus easing the UL FEC operation.

The highway channel is much better than the urban one due to the larger duration of “good” states and increased distance between “bad” states. The UL FEC performance under this channel is shown in Fig. 5. The performance at low elevation angles is comparable to the urban channel; however, as the elevation angle increases, the performance improves much more rapidly than for the urban case. Due to the limitations
in data from the model, the performance can only be plotted over an angle elevation range of 16°–56°. In this example, the maximum interleaver size that is required to correct all errors for speeds is still 10^6 codewords; however, the minimum satellite elevation angle required is reduced to 35°.

C. Narrowcast Mode

As already explained, another PTM mode implemented in the ATB is the narrowcast mode, which is only possible for a small community of users (narrow population), with the narrowcast mode relying on the transmission of negative acknowledgments (NACKs) by MTs to achieve transmission integrity.

If the user group becomes too large, the system gets overloaded by packet repetitions, and it will then not be efficient. Obviously, the bandwidth utilization efficiency will depend on the application, as well as on the narrowcasting date rate and RS coding. The sender may dynamically adjust these parameters through the narrowcast’s QoS descriptors by reflecting the dynamic network metric such as the packet loss rate.

III. ATB ARCHITECTURE

The ATB is an end-to-end hardware-based testbed that is conceived to support a meaningful set of the PTP (unicast) and PTM (multicast) packet-access solutions and is studied and assessed during the initial study phase of the project, in addition to the legacy circuit-switched modes of the RTB.

The ATB, which permits laboratory and over-the-air testing, was conceived to support a client → server IP-based application over an SW-CDMA physical layer by faithfully emulating a two-way (interactive) or one-way (multicast) satellite link between the GW and the MTs.

The GW provides the interconnection to the Internet for interactive services through the ground network or to application-specific servers for specialized services (e.g., multicasting).

The peer client functionalities are supported by the MTs that are utilized by the mobile users. The ATB provides a realistic real-time emulation of the modeled system, whereas the exploitation of software-programmable hardware devices provides a good flexibility with regard to adjusting air-interface parameters.

The emulated operational environment includes multisatellite diversity and beam-handoff capabilities, a comprehensive satellite channel representation, true CDMA interference generation, power control loops, handoff management via ad hoc signaling channels, adaptive interference suppression on the FL, a 3GPP-compliant Turbo codec, and real-time variation of link parameters, in accordance with virtually any user-defined constellation. The top-level ATB architecture is shown in Fig. 6.

The ATB is designed to support 1) PTP two-way services in the circuit and packet modes and 2) PTM services: either the one-way (only involving the FL) or the two-way type (also involving the RL). The first set includes the broadcast/ multicast modes. For the multicast case, an ad hoc powerful upper-layer FEC scheme has been implemented on the FL to achieve high reliability without having to depend on a reliable transport protocol (e.g., transmission control protocol). Two-way services are intended for small user groups, making use of a selective NACK scheme. This last mode is referred to as narrowcast.

To support the above services, the following channels have been implemented in the FL: 1) a DSCH, with dynamic management and open-loop power control, mapped onto the physical DSCH; 2) alternately, the legacy RTB DCH for circuit-mode services, mapped onto the downlink dedicated physical DCH (DL-DPDCH)/DL-DPCCH; and 3) an SSCH, a FACH, and a broadcast channel, all mapped onto the primary common control physical channel (CCPCH).

In the RL, the following channels are present: 1) a RACH-type channel supporting the proposed RASA strategy and mapped onto the physical RACH, or a dRoD channel (dRoDCH) supporting the dRoD strategy described in Section III and mapped onto the physical dRoDCH; and 2) alternately, the legacy RTB circuit-mode dedicated DCH mapped on the UL-DPDCH/UL-DPCCH.

To each RLC, a 15-kS/s DPCCH is associated. Besides the SW-CDMA-compliant modes (operating at the nominal chip rate $R_c = 3.84$ MHz) that are mainly used for laboratory experiments, the ATB also provides reduced chip-rate modes ($R_c = 480/640$ kHz), permitting to carry out over-the-air trials using an existing L-band space segment (e.g., the ESA ARTEMIS L-band land mobile payload), where only a limited bandwidth is available.

Special 70-MHz intermediate frequency (IF) interfaces have been designed for this purpose. Moreover, the over-the-air bit rates are constrained by the EIRP of payload and MTs. Further details on the SW-CDMA physical-layer design can be found in [3], whereas a high-level description about the key ATB subsystems can be found in the following sections.

A. FL Physical-Layer Subsystem

The ATB FL physical-layer subsystem includes the GW modulator unit (GWMU) and the MT demodulator unit.
Fig. 6. Top-level ATB architecture.

(MTDU). The GWMU implements the FL baseband-to-IF GW functionality by generating the SW-CDMA FL waveforms carrying transport channel data received from the MAC layer and transmitted to the MT. The GWMU basically includes channel multiplexing, channel encoding, rate matching and interleaving, spreading, pulse shaping, and IF translation.

To be able to generate CDMA signals corresponding to the three satellites, the GWMU includes three modulators generating the CCPCHs and three pairs of traffic modulators, as required to support diversity and handoffs.

The MTDU implements the FL IF-to-baseband functionality by extracting from the received SW-CDMA waveform the transport channel data and passing them to the MAC layer.

The MTDU supports down-conversion, acquisition, synchronization, despreading, decoding, and demultiplexing. The FL can emulate up to seven beams per satellite (for a total of 21 active beams), although just a single beam per satellite is normally active. However, for limited periods, there can be two active links to support diversity and handoffs. The rake demodulator includes three branches, each branch (“finger”) providing a complete despreader/demodulator function. The fingers include their own IF down-converters, pulse-matched filters, automatic frequency correction, automatic gain control, timing tracking with interpolation, descrambling, and dechannelization for the data and the primary channels. The fingers can be tuned to any of the three signals to be simultaneously processed, thus permitting the three FL channels to be combined. The pilot symbols of the primary channels are used to estimate frequency offset, amplitude offset, chip timing offset (early–late delay-locked loop [17]), and carrier phase and amplitude, as required for MRC. Each finger also includes its own unique-word acquisition unit consisting of a bank of sliding frequency-staggered correlators to cope with the initial carrier frequency uncertainty.

The MTDU also includes a code acquisition unit that is shared by all fingers and is capable of acquiring the spreading code on the basis of the pilot symbols of the primary channel. This unit includes a cascade of coherent and noncoherent correlators integrating the pilot energy across the frequency uncertainty range. The fingers that are currently not involved in signal demodulation utilize the acquisition unit to search for new primary channels in view of possible satellite and beam handoff procedures. The MTDU has also the possibility of operating with a blind minimum output energy CDMA interference mitigating detector unit (IMDU), whose design details can be found in [16]. In this case, the FL scrambling sequence is shortened to allow the operation of the linear IMDU. This optional physical-layer mode is described in [3].

B. RL Physical-Layer Subsystem

The ATB RL physical-layer subsystem includes the MT modulator unit (MTMU) and the GW demodulator unit (GWDU). The MTMU implements the entire physical-layer baseband functionality to generate the true SW-CDMA RL waveform-carrying transport channel data received from the MAC layer and to be transmitted to the peer entity of the GW. Besides modulation, spreading, and pulse shaping, the GWDU is in charge of channel multiplexing, channel encoding, rate matching, and interleaving.

Further details on the RL physical layer and the GW signal processing algorithms can be found in [3]. The GWDU
provides six analog inputs at low IF. Assuming an emulation of a bent-pipe LEO system providing multiple beam/satellite coverage, these inputs correspond to the feeder downlinks of six spot beams with two beams per satellite (the active beam and the next beam the user is handed over to). Some of these six beams may cover the users’ location.

The GWDU consists of two single-user demodulators, each associated to one of the two users. These demodulators are independently operating on the six beam output signals of the RLC simulator unit.

C. Channel Simulator

The ATB satellite channel emulator assembly is designed to support any bent-pipe space segment in orbit, ranging from LEO to GEO satellite constellations. It implements all the required functions and models to emulate the satellite channel with all its signal propagation effects and channel impairments due to the dynamics of the satellite constellation, the motion of the users, as well as the imperfections of the transmission system.

These effects include path delay, Doppler shift, path loss, spot-beam antenna gain rolloff, short- and long-term fading caused by multipath and shadowing, which is typical for the land mobile satellite (LMS) channel, and receiver internal or external thermal noise. This functionality is available in the FL and the RL for three satellites independently and for two users that are located in the same geographic area. Thus, the assembly is capable of simultaneously generating 12 sophisticated complex fading processes, also taking into account the partial correlation between the FL and the RL.

Much effort has been devoted to realistically emulating the LMS propagation, as this is of particular importance to assess the physical- and upper layer performance, including power control schemes. The basic retained approach is the one described in [6] and [8]. It consists of subdividing the signal variations into very slow variations representing large-scale shadowing phenomena (e.g., caused by buildings), slow variations representing smaller scale fading, e.g., inside a shadowed area, and fast (small scale) variations due to a multipath scatter. Fast (Rayleigh/Rician) fading is generated according to the well-known Jakes’ model [9] using an adequate number of numeric oscillators appropriately spaced in the Doppler frequency domain.

D. Interference Generators

In the FL, the ATB also includes a unit that is intended for generating an interference scenario realistically representing a multibeam and multisatellite environment. The generation of true CDMA interference is important to the system performance assessment, in particular, for the FL, where the use of orthogonal code division multiplex techniques as the one used by 3GPP makes the effect of interference not easily approximated by additive white Gaussian noise [22]. In fact, due to the nonfrequency-selective nature of the satellite channel, intra-beam interference will remain orthogonal, whereas other beam interference will be nonorthogonal. This mix of orthogonal and nonorthogonal interference as well as the possible carrier traffic activation with the traffic has an impact on the acquisition, detection, power control, and interference mitigation subsystems; thus, faithfully generating the cochannel CDMA interference in the testbed is needed.

In the RL, multiple-access interference as normally present in a real system is also directly added after the channel emulators via the CDSU. The so-called MT interference simulator unit is based on an arbitrary waveform generator reproducing realistic cochannel and adjacent channel interference originating from a multitude of other users that are located in the same or adjacent satellite spot beams.

E. Upper Layers

The task of the ATB “upper layers” is to provide an interface between the FL and RL physical layers and the application layer. As the interface to the application layer can support any transport layer protocol on top of IPv4, virtually any Internet application can be used with the ATB if it can cope with the data rates and transmission delays provided by the testbed. The GW and the UTs operate as IP routers; however, the UTs do so in a limited fashion since the only peer they can directly communicate with is the GW. Thus, any traffic between two UTs is routed via the GW.

For multicast group membership management, the standard Internet group management protocol (IGMP) is used. In contrast to the normal multicast routing setup, where different multicast routers use multicast routing protocols like distance vector multicast routing protocol or protocol-independent multicast to communicate with each other, the ATB uses a simplified scheme whereby the IGMP membership messages are forwarded by the routers in the UTs to the GW router. Essentially, the whole ATB network is treated as the last hop by the GW, which is always informed about the group membership of its UTs. This enables efficient use of the multicast features provided by the ATB physical layer, and it also dramatically reduces the messaging overhead that normally exists between neighboring multicast routers. This optimization can be done taking into account that a satellite system like the ATB is a PTM system with known topology. The ATB supports basic QoS by assigning different priorities to IP packets based on their type-of-service field.

IV. CONCLUSION

In this paper, we described in some detail the key design drivers of a comprehensive S-UMTS real-time testbed (the ATB) based on an adaptation of the 3GPP W-CDMA standard that is needed to cope with the satellite environment. The ATB is designed to faithfully reproduce complex satellite mobile constellations (from LEO to GEO) and channel impairments in a laboratory environment.

The ATB supports a wide range of services, ranging from reliable multicast to unicast packet access in addition to the more conventional connection-oriented modes. Also, a rich suite of applications exploiting the supported services have been developed for S-UMTS applications demonstration and
QoS assessment. The ATB performance measurement results that are obtained in the laboratory and over the air are summarized in a companion paper [18].

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REFERENCES


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