WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2002; **2**:301–316 (DOI: 10.1002/wcm.59)

Uplink–downlink design issues for next generation satellite networks

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Summary

Next Generation Mobile Systems will implement one's dream of anywhere, anytime communications. Providing global coverage and mobility, satellite systems will play an important role in order for this to be achieved. The design options of satellite systems include several choices. The basic ones are the choice of orbit, processing and switching, intersatellite links, and link layers technologies. In addition to the network architecture, the protocols must be developed for efficient use of the satellite radio resources. The most important protocol design issues concentrate on Medium Access Control (MAC) techniques, routing and traffic management. In this paper some of the special features of satellite systems are considered. Emphasis is given in MAC protocols design, as well as in research programmes that led to their development. Finally, an adaptive hybrid access scheme that combines CDMA technology and random access techniques is presented. This new scheme is called CDMA/PRMA and from the results obtained it is a very promising access technique for next generation satellite systems. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS

satellite systems
uplink–downlink issues
research efforts
TCP/IP
multicast
ATM
MAC CDMA/PRMA

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1. Introduction

We are moving into a new era of communications and information technology. The newest ingredient of the telecommunications system is mobility. Customers will want to combine mobility with multimedia, resulting in higher demand for bandwidth and creating a significant shift towards new data services. Meeting complex and growing user demands, is the major and urgent challenge for the world telecommunications industries and organizations into the 21st century [1].

Third Generation Mobile Systems will implement one's dream of anywhere, anytime communications with a lightweight and convenient pocket communicator and this is certainly the main purpose of IMT-2000 [2]. It will also expand the range of services since wireless facilities of the future must be able to provide, in addition to high quality voice communications, a variety of data services in order to offer a wide range of applications (ranging from Internet access to file transfer and video conferencing) [3]. Of course, in order to achieve such a service variety, broadband transport technologies have to be used (in opposition to narrowband ones used in today's second generation mobile systems). To fulfill such multimedia services, a bit rate of 2 Mbps has been proposed for IMT-2000 for the first phase and another one of 20 Mbps has been envisaged for a future development. Systems '*beyond IMT-2000*', which will primary have market impact beyond 2015, will be able to support bit rates in the range of 100 Mbps. For these systems there may be a requirement for additional spectrum (globally harmonized) sometime after 2010. (WARC'92 designated the frequency bands 1885–2025 MHz and 2110–2200 MHz for the IMT-2000 for the terrestrial and the satellite component respectively [4]).

The vision for the further development of mobile communications beyond third generation, will mainly been driven by user perspective. Personal Area Network (PAN) [5] will connect the user with all carried devises like camera, phone, mirror glasses for images etc., in a short-range connectivity. The immediate environment like a TV, a PC, a refrigerator will also be connected to the user, who will also have the ability for direct communication with other users or vehicles. Different radio access systems like terrestrial systems, satellite systems and High Amplitude Platform Stations (HAPS) will provide full area coverage. Therefore the different communication relations between person to person, machine to person and vice versa and machine to machine, will determine mobile and wireless communications in the future [6].

According to ITU the initial goals of 3G networks and beyond are to provide limited inter-operation of global standard families, global multimedia services from indoors picocells to satellite megacells and to realize global multimedia service round the clock. The satellite segment will achieve global seamless coverage in outdoor environment, meanwhile will keep compatibility of user terminals and transportability of services. The major goals of S-IMT-2000 and beyond are to realize global roaming, quality of service (QoS) comparable to terrestrial systems at reasonable cost and finally to ensure full coverage anytime, anywhere.

The next generation of satellite systems will have a total capacity in the giga-bit-per-second while systems, in the planning stage at the moment, are claiming capacities in the terra-bit-per-second. It has to be cleared that satellite systems cannot compete with the capacities, and with the channel qualities, which can be achieved in fibre optics systems. However, the special features and advantages of satellite communications such as broadband interconnectivity for widely dispersed users with greater ease and simplicity than an infrastructure based on terrestrial broadband links, point-to-multipoint transmissions etc., will guarantee an increasingly important role for satellites as part of a Global Information Infrastructure (GII).

Since 1990 the satellite communication field has entered a major new area, with a large number of global and regional systems in operation, development, or design stages. Intelligent satellites with onboard processing capabilities and of constellations in different orbits (LEO, MEO, ICO, GEO) are connected to each other to act as network in the sky and provide global coverage and the ability of global mobility. Different frequency bands have been assigned to different constellations. At L/S band, LEO satellite networks are experiencing an enormous growth for personal voice and low data services. For the satellite segment of the Universal Mobile Telecommunications Systems (UMTS), which is one of the major new third generation systems being developed within the framework that has been defined by the ITU and is known as IMT-2000, part of the S frequency band has been allocated. Furthermore, the growing need for multimedia services in high-rate transmissions pushes into higher frequency bands, namely Ka-band and even beyond at extremely high frequencies (EHF) where the use of GEO systems is developing very fast [7,8].

The design options of satellite systems include several choices. The basic ones are the choice of orbit, processing and switching, intersatellite links (ISLs), and link layers technologies. In addition to the network architecture, the protocols must be developed for efficient use of the satellite radio resources. The most important protocol design issues concentrate on Medium Access Control (MAC) techniques, routing and traffic management [9]. The satellite, as a shared resource, must be cooperatively used by its users. Thus, to avoid interference in the uplink, there is a need to use appropriate multiple access schemes. Different access schemes for applications in satellite systems have been proposed in literature based on classical Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access and hybrid schemes (i.e. a combination of these basic multiple access principles) [10]. The CDMA technique has been chosen in third generation mobile networks. Several mobile satellite systems will use CDMA schemes for their land–mobile links (Globalstar, Skybridge). While it does not appear to be a single access scheme, there are some characteristics that give CDMA certain distinct advantages, especially in mitigating multipath fading of the radio link and interference from other systems. In Reference [77] a joint Code Division Multiple Access/Packet Reservation Multiple Access (CDMA/PRMA) technique has been introduced as a candidate for 3G terrestrial networks and in Reference [76] the authors have successfully presented the performance evaluation of PRMA in LEO satellite networks. In this work we propose an adaptive CDMA/PRMA protocol for application in LEO and MEO satellite systems.

This paper is organized as follows. Section 2 reports some recent and continuing research efforts on satellite systems, which are mainly supported by the European Union. Section 3 presents some of the technical challenges involved with next-generation satellite systems by giving emphasis on the selection of the multiple access scheme, which is of great importance for satellite networks. Finally, in Section 4, the CDMA/PRMA technique is presented and simulation results are discussed.

2. Research Effort In Europe

2.1. The Fourth Framework Programme

During the past decade some important field trials have been performed in Europe to demonstrate satellite multimedia services. Under the 'Fourth-Framework Programme of European Community activities in the field of research and technological development and demonstration (FP4, 1994–1998)' the Advanced Communications Technology and Services (ACTS), played a major role in developing and experimenting the technology, including satellite access [11]. One of the specific objectives of the ACTS programme was to develop design and study advanced technologies and systems for satellite communications. Many projects led by the ACTS Programme have contributed their research efforts on third generation satellite communication systems. In the next paragraphs some of the projects that deal with satellite networks are briefly described.

Within the TOMAS (Inter-trial Testbed of Mobile Applications for Satellite Communications [12]) project a broadband mobile satellite access platform was developed, based on the Asymmetric High Speed Data Pilot System developed in the RACE II Project MOEBIUS (RACE: Research into Advanced Communications for Europe, 1985–1995). This trial platform was composed of an L-band terminal, Inmarsat capacity and interconnection with ISDN. This platform was made available to other projects for running pilot experiments. Furthermore, through the TOMAS project, a lot of trials have been done on satellite systems to support services, first developed for the terrestrial UMTS segment, as MPEG-4.

The SINUS (Satellite Integration into Networks for UMTS Services [13]) project is aimed at maximizing harmonization with the terrestrial standards, thus allowing for the production of inexpensive multi-mode satellite/terrestrial terminals. The SINUS project managed to define and develop W-CDMA-based air interface protocols, following closely the terrestrial UMTS air interface. Furthermore, an advanced satellite channel emulator was developed for future satellite constellations.

SECOMS/ABATE (Satellite EHF Communications for Mobile Multimedia Services / ACTS Broadband Aeronautical Terminal and Experiment [14]) projects focused on the investigation of a new generation satellite system that would be able to provide broadband services to portable and mobile small-sized terminals. The payload, allocated on geostationary satellites operated at Ka and EHF frequency bands, with on-board processing and multibeam antennas.

The SUMO (Satellite-UMTS Multimedia Service Trials over Integrated Testbeds [15]) project aimed to succeed the interoperability between real and simulated satellite systems (LEO, GEO) with the terrestrial core networks (B-ISDN) in order to approach the idea of the UMTS. Different issues were studied, such as the automatic selection of alternative access network resources depending on services and mobile environments, bandwidth on demand, different access schemes (CDMA, FDMA). The project developed a satellite-based UMTS testbed by combining and improving two ACTS testbeds developed in the SINUS and TOMAS projects.

WISDOM (Wideband Satellite Demonstrator of Multimedia Services [16]) was another project, which has been focused on Ka-band satellite access for broadband applications. Within the project a complete end-to-end ATM network testbed was also developed.

2.2. The Fifth Framework Programme

Under the 5 FP, which is a research, technological and demonstration programme (RTD) of the European Union, a set of common criteria reflecting the major concerns of increasing industrial competitiveness and the quality of European citizens have been set. The 5 FP covers the period 1998–2002. The 'thematic' programmes are focusing on the following priorities: (1) improving the quality of life and the management of resources of the living world; (2) creating a user-friendly information society; (3) promoting competitive and sustainable growth; and (4) preserving the ecosystem. The work carried out in previous thematic programmes by the end of the 4^{th} FP such as ACTS, Telematics and Esprit, will be continued mainly in the scope of the Information Society programme (IST) [17].

IST is just an integrated research programme with the main objective of the convergence of information processing, communications and media technologies. This will enable citizens to access IST services wherever they are, whenever they want, and with simplicity. A specific area of the IST programme is the *Integrated Satellite Systems & Services* where new technologies and architecture will be developed in order to deliver interactive multimedia services through satellites. Within the IST many programmes have been started focusing on next generation satellite systems. Most of these projects are briefly described below.

The SATIN (Satellite-UMTS IP-based Network [19]) project is expected to introduce a novel concept for the satellite component of UMTS, which will provide a range of new packet-based and point-to-multipoint services, to the T-UMTS. In addition to the SATIN project the SATIN Kiosk project will provide high speed and multicast services for information kiosks at frequently attended places such as village centres, bus stations and rest areas, deploying a return channel satellite system.

The VIRTUOUS (Virtual Home UMTS on Satellite [20]) project aims to identify, design and demonstrate a smooth migration path towards Terrestrial and Satellite UMTS segments. Therefore any user travelling through various access networks will have the ability to change them with ease, as if the user was roaming on their home network.

The BRAHMS (Broadband Access High data rate Multimedia Satellite [21]) project aims to define a generic user interface (user terminal to satellite terminal) and a Radio Independent Access protocol for Broadband Multimedia Satellite Services. This universal access interface for Broadband Satellite Multimedia service will be open to different constellations (e.g., LEO, GEO). High bit-rates of up to 150 Mbps will be provided to users.

The MULTIKARA (Multibeam Ka-Band Receiving antenna for future 'Multimedia via satellite, direct to home' systems [22]) project concentrates on the design and implementation of suitable antennas for the next-generation multimedia satellite networks operating in the Ka-band.

The GAUSS (Galileo And UMTS Synergetic System [23]) project will define and integrate navigation/communications system fitted with the S-UMTS framework, which is based on the Galileo system (European navigation system). GAUSS will also try to develop a 'demonstrator testbed' in order to provide a realistic implementation and support the proposed integration.

3. Issues in Satellite Networks

The design options of future satellite systems include several choices. The choice of suitable constellation, intersatellite links, processing, ATM and TCP/IP via satellite, selection of a multiple access scheme are just a few basic issues for satellite systems. In the next paragraphs a brief detail of them is denoted by giving emphasis on the selection of suitable MAC (Medium Access Control) layer access schemes.

3.1. Constellation Selection

The constellation selection is constrained by many factors such as the round trip delay (RTD), mainly dependent on the orbit altitude, the satellite weight and mass and the additional cost, the complexity, the network topology, the bit-rate capability, the earth coverage and many more.

The high RTD of GEO (Geostationary Earth Orbit) satellite systems make them unsuitable for real-time communications. On the other hand the high capacity they can offer make them suitable for services such as multicasting and broadcasting [24]. LEOs and MEOs (Low Earth Orbit, Medium Earth Orbit) are suitable for real time, delay-sensitive services due to the lower altitude than GEOs. On the other hand in such systems there is the need of many satellites and earth stations to provide global coverage of the earth, and much more complex networks.

While GEOs are always in sight of a terrestrial gateway by virtue of an orbit that matches the earth's rotation and MEOs are overhead for 2–4 h, LEOs tend to be overhead for less than 15 min before having to perform complex airborne traffic handoffs to another satellite. That short span also means that LEO earth stations must use phased-array antennas that maintain an active link by keeping at least two satellites in view at all times. The antenna starts a new link before severing one with a satellite moving out of range, all of which adds to terminal complexity and cost. On the other hand, because GEOs are further away, they need to incorporate more power supplies on their transmitters, increasing the cost in this way.

Thus, mixed constellation of GEOs and non-GEOs might be suitable for next-generation satellite systems combining both of their advantages.

3.2. Intersatellite Links (ISLs)

An intersatellite link (ISL) is a direct connection between two satellites in space with the use of high frequency RF links or optical links [25]. The use of optical ISLs gains much research interest nowadays. One significant factor in this trade-off is that the optical system will typically have a much narrower beamwidth than the RF system. This has both a positive and negative side. On the positive side, a narrower beamwidth means that the potential for interference to or from adjacent satellites will be reduced. This is particularly important in large LEO constellations. On the negative side, the requirements for more accurate pointing, acquisition and tracking (PAT) and the impact that this may have on the spacecraft could impose an unwelcome burden. Accurate PAT is critical to the acceptance of optical ISLs. A secondary, though not unimportant, fact about optical communications is that, unlike the RF spectrum, which is regulated by national and international agencies, the optical spectrum is currently unregulated [26].

Routing of traffic packets in satellite systems can be achieved not only through earth stations but also through neighbouring satellites (in the same orbit: intra-plane or in adjacent orbits: inter-plane) with an intersatellite link process on board [25,27]. This allows a user terminal on the ground below the satellite to exchange traffic with gateways to the terrestrial network or with users below distant satellites not visible to that terminal, without requiring a local gateway or significant terrestrial infrastructure to do so. This way, the shortest path might be provided, improving the performance of the system and reducing also the number of gateways stations.

On the other hand the design of the space-based constellation network is restricted by the constraints imposed by orbital geometry and the difficulties in implementing networking in the space segment (e.g. the antennas must be re-directed).

Commercial and proposed systems utilizing ISLs include Motorola's deployed LEO *Iridium* [28] constellation, the proposed LEO *Teledesic* [29] constellation, Hughes' GEO *Spaceway* and the MEO *Spaceway NGSO* proposals [30] and the GEO *Astrolink* proposal [31,32].

3.3. TCP/IP via Satellites

Due to the enormous growth of the Internet new and faster access to it are demanded. Satellites could play an important role to this demand as they can offer high-bandwidth connections to a large geographic area with little cost.

TCP/IP is the general term used for the suite of protocols upon which the Internet depends. IP, the Internet Protocol, provides a connectionless datagram service that enables packets to be routed to their destinations by inspection of header information. TCP, the Transmission Control Protocol, makes reliable ordered communication of streams of data, such as files, possible by implementing a duplex protocol, based around sliding windows and acknowledgements, over IP [33].

The evaluation performance of TCP/IP protocols over satellite systems has already been approached [34,35]. TCP/IP implementations have been shown to work well over satellite links, as experiments with TCP/IP over ATM on the NASA ACTS satellite [36]. However, the large latencies, bandwidth and path asymmetries [37], and occasionally high error rates on satellite channels make TCP/IP approach over satellites quite difficult.

Over the past decade, a number of TCP extensions have been specified which improve upon the performance of the basic protocol in high latency environments such as satellite networks. Some of them are mentioned below: Window scale [38], Selective Acknowledgments (SACK) [39], TCP for Transactions (T/TCP) [40], Path MTU discovery [41]. Furthermore, the IETF (Internet Engineering Task Force) is in the process of creating an informational standard that identifies which standardized TCP options should be used in future implementations [42]. Partridge and Shepard also discuss some of these transport improvements [43].

3.4. ATM via Satellite

ATM (Asynchronous Transfer Mode) was introduced as the underlying technology of the developing B-ISDN [44]. B-ISDN is being implemented currently and is still developing as an extremely high bandwidth technology. The aim of B-ISDN is to support all forms of current and future telecommunications traffic, such as, but not limited to: telephone calls, videoconferences, television broadcasts and Internet services, within a single integrated network. With all these services in mind, ATM has been developed as a technology that embraces cell-switching technology. Cell-switching has many benefits over circuit-switching. Cell switching easily handles both constant rate and variable rate traffic at very high rates and importantly, it supports point-to-multipoint broadcasting, which is required for television distribution and cannot be provided by circuit switching.

Satellite networks offering broad geographical coverage and fast deployment appear to be an attractive option for the next-generation integrated broadband communication networks based on 'ATM-like' technology (means that packets of fixed size will be used but not as 53 byte ATM cells). The use of satellite to carry ATM traffic presents a number of unique problems due to the nature of the satellite link. The bit error rate, propagation delay and bandwidth characteristics are the major problems in satellite links supporting ATM.

The integration of the terrestrial B-ISDN with the satellite segment is quite difficult due to the higher error rate in satellite links [45–47]. The ITU-R Recommendations for Satellite Communications specify a BER of 10^{-7} at 96 per cent of the time, while for the specifications of performance over a fibre link specify a BER of 10^{-9} at 99.9 per cent of the time. It must be mentioned here that through the use of coding schemes such as Reed–Solomon, BERs of greater than 10^{-10} can be achieved. Satellite can therefore achieve the 'fibre-like' performance required for ATM service. However, there is a fundamental difference in the nature of errors, which also must be considered in order for proper ATM performance. For most terrestrial microwave and fibre networks it is assumed that bit errors are randomly distributed. In satellite links bit errors are likely to occur in bursts. Since the ATM header error check (HEC) is able to correct single bit errors, the burst errors in the ATM header cannot be corrected. Therefore, there might be a significant increase in discarded ATM cells due to uncorrectable errors. One technique developed, which provides significant reduction in cell discard probability, is Comsat Laboratories ATM link enhancement (ALE) [48]. ALE uses Reed–Solomon coding and a selective bit interleaving technique. The burst error characteristics can also affect the performance of ATM adaptation layer (AAL) protocols [49,50]. AAL maps user data into a format, which can be passed to the ATM layer for transmission. Some of these protocols employ cyclic codes for error detection. AAL1 and AAL3/4 employ 3-bit and 10-bit CRCs (Cyclic Redundancy Check), respectively while AAL5 employs a 32-bit CRC, which is more powerful in burst error detection. Therefore, AAL5 appears to be more suitable for a satellite environment. However, there might still be severe discarding of cells at the physical level, and there is a need to compensate for this by using interleaving mechanisms, error recovery algorithms or efficient coding schemes for error correction.

A satellite communication link produces a significant propagation delay due to the high altitude of satellites. This additional delay can impact the operation of network protocols by affecting various functions such as acknowledgements, timeouts and the timely dissemination of network management information. This delay can significantly increase the latency of mechanisms, which are used to manipulate traffic congestion problems. Two current congestion control functions are Selective Cell discard and Feedback, which may have problems when operating in an ATM satellite environment. For example, the retransmission mechanism of discarded cells in the first method could significantly delay the delivery of a large number of other packets. On the other hand in the feedback mechanism the sender must be notified if it is responsible for the congestion and reduce its traffic. This notification increases the overall delay.

There are different feedback mechanisms. The Backward Explicit Congestion Notification (BECN) could be preferable in satellite links as the notification to the sender could be sent in the reverse direction of the congested path [51,52].

Current satellite capabilities appear adequate to support the initial introduction of ATM into the backbone network. However, if satellite is to play an important role in the next generation of ATM-based telecommunications networks, new satellite architectures based either on a non-processing satellite system, or with onboard ATM processing, have to be developed [53].

3.5. Multicast over satellite

One of the major applications of next-generation satellite systems will be the multicasting. Multicast allows a source to send data simultaneously to all hosts on the internetwork where users are interested in receiving the data, but in a more efficient manner than simply flooding the entire internetwork with redundant broadcast packets. Satellites that can easily send information to widely dispersed users are suitable for such applications. There is a considerable interest and research in multicast protocols such as ATM multicast [54] or IP multicast [55]. The former one is less mature than the latter. In Reference [56] the authors summarize early implementations, while References [57] and [58] overview the development of multicast and provide a taxonomy of protocols.

Efficient use of satellite constellations for group applications hence requires satellite onboard switches including support for multicast. However, given the assumption that at least the first generation of broadband systems (Ka-band) will probably select technologies that do not rely heavily on sophisticated and risky onboard processing, it appears unlikely that IP multicasting support will be available in commercially proposed schemes in the near future.

3.6. Medium Access Control (MAC) Layer protocols

Satellites, as shared resources, must be cooperatively used by its users. To avoid interference from other users, a procedure must be invoked to distribute packet transmission among users. This procedure is well known as a Medium Access Control (MAC) Layer protocol.

MAC protocols are often classified by their resource sharing as well as the method they divide the resources into accessible segments [59,60]. According to the way they share the resource they can be classified as:

- *Dedicated assignment*: A predetermined and fixed allocation of resources is assigned to users, regardless of the need of the users to transmit. Dedicated assignment techniques are suitable for continuous traffic but inconvenient for bursty traffic.
- *Random access*: In random access schemes transmission of packets is possible as soon as a user has packets available to send. The main characteristic of these schemes is the contention for the channel. Random access is suitable for bursty traffic but unsuitable for delay sensitive traffic.
- *Demand-based assignment*: In these schemes resources are assigned to users if they have already made a request or a reservation of them. Demand assignment channels are suitable for variable rate traffic but additional overhead and delay caused by the reservation mechanism that has been followed could degrade the performance of these protocols.

As far as the method that is used to divide the resources is concerned, according to References [59,60] three methods are basic: (1) Frequency Division Multiple Access (FDMA); (2) Time division Multiple Access (TDMA); and (3) Code Division Multiple Access (CDMA).

In FDMA schemes the available spectrum is divided into segments (channels) each of them is dedicated to different users. FDMA has been used for decades in ‘bent-pipe’ satellites for uplinking and downlinking of analog signals such as telephone conversations in INTELSAT systems [61]. In TDMA the resource is divided into time slots. Users are assigned different time slots for transmitting their packets on a common frequency. In the case of satellite systems, when the access scheme is the TDMA, the need for synchronization is necessary in order for the transmitted packets to arrive at the satellite at the correct times. Finally, in CDMA-based schemes a collection of codes is assigned to users so they can coexist in the same channel (same frequency band). Hybrid versions combining the above techniques are also possible. In Reference [62] several hybrid techniques are presented. The authors have mainly focused on the combination of spread spectrum techniques with random access protocols providing more efficient ways to invoke different sources of traffic (voice, data, video) as well as improving the performance of the system.

In recent years there has been considerable debate on the issue of whether TDMA or CDMA is the best candidate for 3G networks and beyond. As far as the future satellite networks are concerned the European Space Agency (ESA) has submitted two possible Radio Transmission Techniques (RTT) to ITU (International Telecommunication Union) as candidates for the IMT-2000 air-interface [63]. These techniques were the SW-CDMA (Satellite Wideband CDMA) and the SW-CTDMA (Satellite Wideband Code TDMA). For global coverage including mainly LEO and MEO networks the first proposal was found more suitable in adapting the terrestrial ETSI UTRA/ARIB W-CDMA proposals to the satellite environment. On the other hand, for regional systems consisting of GEO or HEO, SC-TDMA was found more efficient and shows some commonality with ETSI UTRA TDD [64].

Besides the conventional TDMA and CDMA access schemes there are some other techniques which might have a better performance in next-generation, broadband mainly, satellite networks. As has been shown in Reference [61] Multi Frequency-TDMA (MF-TDMA), which is the combination of FDMA and TDMA, increases the satellite network bandwidth and reduces the amount of transmitted power. Many designers of future broadband satellite networks (COMSAT, Teledesic) are considering the use of MF-TDMA, due to the fact that it can offer attractive features such as 'on-demand' allocation bandwidth. This could be useful for satellite systems supporting ATM traffic [65,66] (implies bandwidth on demand). A detailed analysis of MF-TDMA satellite systems can be found in Reference [67]. Multi Carrier-CDMA (MC-CDMA) is another access technique that is gaining more support by the day. MC-CDMA combines the Orthogonal Frequency Division Multiplexing (OFDM) characteristics with the CDMA [68,69]. MC-CDMA, as in Reference [70], can be further classified in two main classes: spreading in the frequency domain, and spreading in the time domain. The former is denoted as MC-CDMA and the latter as MC-DS-CDMA. This technique is different from DS-CDMA in that it uses several parallel carriers to deliver the user information thus is even more resistive to fades and signal loss [71]. In Reference [72] there has been an approach of the use of MC-CDMA techniques over LEO constellations.

Next-generation communication systems must be able to provide real-time and non-real-time services to users. In order to achieve this, efficient MAC protocols must be implemented supporting, for example, voice and data packet services. CDMA plays an important role due to its inherent signal diversity and its resistance to multipath fading. Especially the combination of CDMA with other access schemes can provide hybrid access techniques with characteristics suitable to manipulate different kinds of traffic. Specifically, the combination of CDMA with PRMA (Packet Reservation Multiple Access) access scheme, as has been shown in Reference [77], could be a promising candidate for next-generation terrestrial systems. On the other hand, the conventional PRMA protocol has a great performance for LEO satellites systems as has been shown in Reference [76]. Also [73], there has been a first approach to implement the CDMA/PRMA protocol in a LEO system. It resulted that this technique has a good performance in such an environment and has a similar performance compared with the terrestrial one. The main objective of the next-generation system is the convergence of the terrestrial and satellite segment in order to provide global coverage and mobility. This MAC technique could be an efficient candidate for such systems, due to its compatibility of the terrestrial and satellite environments. In this work an adaptive DS-CDMA/PRMA is proposed for a LEO constellation with extensions to an MEO environment.

4. The CDMA/PRMA Protocol

A LEO constellation is assumed where information is provided in the downlink about the status of the radio channel. Earth stations are responsible for transmit permission control procedure and they resolve problems like resource allocation. Perfect power control is assumed and all downlink signals can be received by terminals without failure. The proposed CDMA/PRMA access scheme is an extension of the conventional PRMA in a DS/CDMA environment [74,75]. Essential parameters for the Satellite constellations have been taken from Reference [76], where the successful application of PRMA has been proved for a *limited* number of users.

User terminals can send three types of information: 'Periodic', 'Random', and 'Continuous'. Speech packets are always periodic; data packets can be random (isolated packets) or periodic (mail, small files), and video packets are continuous. The time axis in the channel is divided into equal time frames and each of them is consisted by equal number of time slots. Periodic sources generate one packet per frame, so the number of time slots per frame [76] is equal to $N = \left\lfloor \frac{R_p T_f}{R_s T_f + H} \right\rfloor$ slots/frame and $Ts = \frac{T_f}{N}$ [ms], where $\lfloor x \rfloor$ denotes the biggest number less than or equal to x, T is the frame duration, R_p is the PRMA channel bit rate and R_s is the source bit rate.

On the uplink, information channels are separated by different spreading codes and the number of codes denotes the Multiple Access Capability (*mac*), which is the maximum number of packets that can be correctly received simultaneously at the satellite, and it is limited by MAI (Multiple Access Interference). Namely, all packets are considered to be destroyed if the number of simultaneous transmissions in a slot exceeds *mac*.

4.1. CDMA Environment

The footprint of the satellite is subdivided into multi-spot-beams, by using multi-beam antennas, with different frequencies in neighbouring beams to avoid intercell interference. As in Reference [77], the performance of a CDMA system is measured by the bit error ratio (BER) factor and any problems related to packet acquisition are ignored. To determine BER the standard Gaussian approximation is used. Assuming that MAI is Gaussian and perfect power control is employed, the BER $P_{\text{error}}(K)$ in the case of no Additive White Gaussian Noise (AWGN) can be obtained by Equation (1).

$$P_{\text{error}}(K) = Q\left(\sqrt{\frac{3^* SF^* P_0}{(K-1)^* P_0 + \sum_{k=1}^{K}\sum_{i=1}^{R} P(k,i)_0}}\right) \tag{1}$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-u^2/2} \text{du} \tag{2}$$

where $Q(x)$ is obtained by Equation (2), SF is the spreading factor and K is the number of packets transmitted simultaneously in each cell (spot beam). P_0 is the received power level at the satellite and $P(k, i)_0$ is the interference power from users outside a given spot beam. As has been mentioned above, different frequencies are used in neighbouring spot beams so $P(k, i)_0$ is neglected. Thus Equation (1) is substituted by Equation (3).

$$P_{\text{error}}(K) = Q\left(\sqrt{\frac{3^* SF}{(K-1)}}\right) \tag{3}$$

When packets of length L bits are transmitted over a radio channel with $P_{\text{error}}(K)$, the packet success rate $P_{\text{success}}(K)$ is given by:

$$P_{\text{success}}(K) = [1 - P_{\text{error}}(K)]^L \tag{4}$$

In general, as in Reference [77] the packet success probability in a given slot depends on the number of transmissions, the amount of Forward Error Correction (FEC), and the spreading factor. In this work no block code has been employed, so the packet success rate in single spot-beam can be approximated by the simple function:

$$P_{\text{success}}(K) = \begin{cases} 1, K < \text{mac} \\ 0, \text{otherwise} \end{cases} \tag{5}$$

As in References [75,76,78] using a packet of $L = 256$ bits length and $SF = 8$, if $mac = 6$ is chosen, packet success rate $P_{\text{success}}(K) >= 0.99$ is satisfied, which is the maximum value received in our analysis for the chosen parameters (Figure 1).

4.2. Voice–Data Subsystem

For voice terminals a slow speech activity detector is assumed, which reveals only principal gaps during the conversation [74,75]. Due to the slow speech activity detector, a conversation is divided in talking and silent phases and can be modelled by a Markov chain. Exponential distributions with expected values of 1 s and 1.35 s respectively for the talking phase and the silent Phase have been used for modelling the states. The voice packets are created periodically only during talkspurts at a rate of one packet per frame. Due to the time sensitivity of voice, speech packets exceeding the allowable maximum delay $D_{\max}$ are dropped and the terminal tries to obtain reservation for the next packet. If reservation has been achieved the terminal maintains the slot until the end of the current

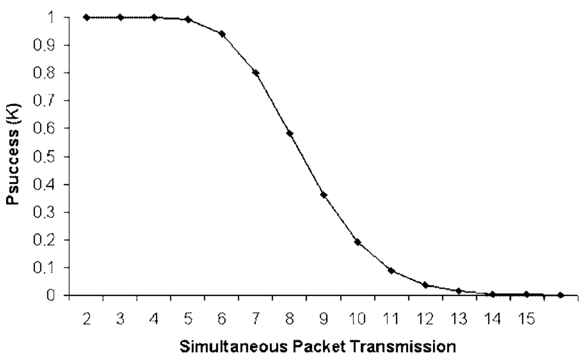

Fig. 1. Packet success rate.

talkspurt. The end of this talkspurt is communicated to the satellite by sending as in Reference [78] an end-of-use flag. The satellite releases the reservation of a slot when it recognizes the end-of-use flag and informs in the downlink all the contending terminals. Using such a control, reservation cancellations due to excessive MAI can be prevented.

The quality of the voice transmission with CDMA/PRMA is measured by the probability of packet loss P_{loss} that is the probability that a packet is dropped off the buffer due to a long wait time (longer than $D_{max)}$ or due to corruption because of excessive MAI. Corrupted or dropped packets are not retransmitted. With contemporary speech codecs, it is required that $P_{loss} < 1$ per cent for a low degradation of speech quality.

Data terminals as in Reference [76] produce messages according to independent Poisson processes with mean rates λ. Every message has a random length and it is segmented in packets. The number of packets follows a geometric distribution. A data terminal maintains a successful reservation until it transmits all its messages in the buffer. The parameter, which measures the performance of the data subsystem, is the average message transmission time, T_{msg} that is the mean time from the message arrival to the buffer to the instant of its complete transmission.

4.3. Channel Access

Terminals in contention mode perform a Bernoulli experiment with the current permission probability as the parameter. They transmit a packet if the outcome of the Bernoulli experiment is positive.

The access permission probabilities are modified slot by slot, depending on the number of packets with reservation and the number of contending packets. Instead of using the channel access function, which was applied in the conventional CDMA/PRMA [77], in this work an adaptive permission probability algorithm is introduced. As in Reference [76] in this work for a LEO constellation the Round Trip Delay (RTD) is taken equal to the frame duration. In a MEO constellation the RTD is longer due to higher altitude of the satellites. Moreover, the RTD usually varies during the service of a talkspurt/message due to the satellite constellation dynamics.

In Reference [75] the authors have assumed that a speech terminal contains a first-in–first-out buffer to store packets awaiting transmission. If the buffer is full when a new packet arrives, the terminal drops the oldest stored packet and stores the new packet. It then attempts to transmit the oldest remaining packet. The buffer size required for this dropping mechanism is: $PB = \lceil D_{max}/T \rceil$, where $\lceil x \rceil$ denotes the smallest integer $> = x$. T is the frame duration and D_{max}, the maximum transmission delay for voice packets. In this work assuming that $D_{max} = 32$ ms and $T = 16$ ms the buffer can store only two packets.

In recent studies when a voice packet lacks permission to transmit in one slot the next trial can be done in the same slot in a subsequent frame because the frame and arrival rates are equal [79]. Taking into account that a two-packet buffer is available, in this study a voice packet can try more than once for a reservation until the time of trials exceeds D_{max}. Voice packets are restored in a two-position FIFO buffer. The waiting time must be random or the same packet will try again in the next frame in the same slot, increasing the amount of tolerable delay that a voice packet can wait due to time constraints.

Introducing such a policy the number of dropped voice packets is decreased because the time to gain a reservation is reduced. The random amount of time that a packet waits in the terminal's buffer can be modelled by different distributions. In this work an exponential distribution is assumed with mean time a frame duration (Figure 2).

4.4. The Proposed Adaptive-Access Permission-Probabilities Algorithm

Permission probabilities are dynamically modified by observing the channel status. The satellite in the downlink informs all the terminals about the status of the channel by sending information at the end of each slot on: (a) the number of reservation voice packets (NORVP), (b) the number of reservation data packets (NORDP), (c) the number of contending voice packets (NOCVP), (d) the number of contending data packets (NOCDP), and (e) the number of available codes (NOAC) (equal to the number of multiple access capability minus the number of voice and data packets with reservations). Voice and data terminals having all this information are counting their permission probabilities for an attempt in the same slot in a subsequent frame.

The proposed algorithm is described below:

Step 1: The satellite broadcasts the values of NORVP, NORDP, NOCVP, NOCDP, NOAC and the initial permission probabilities.

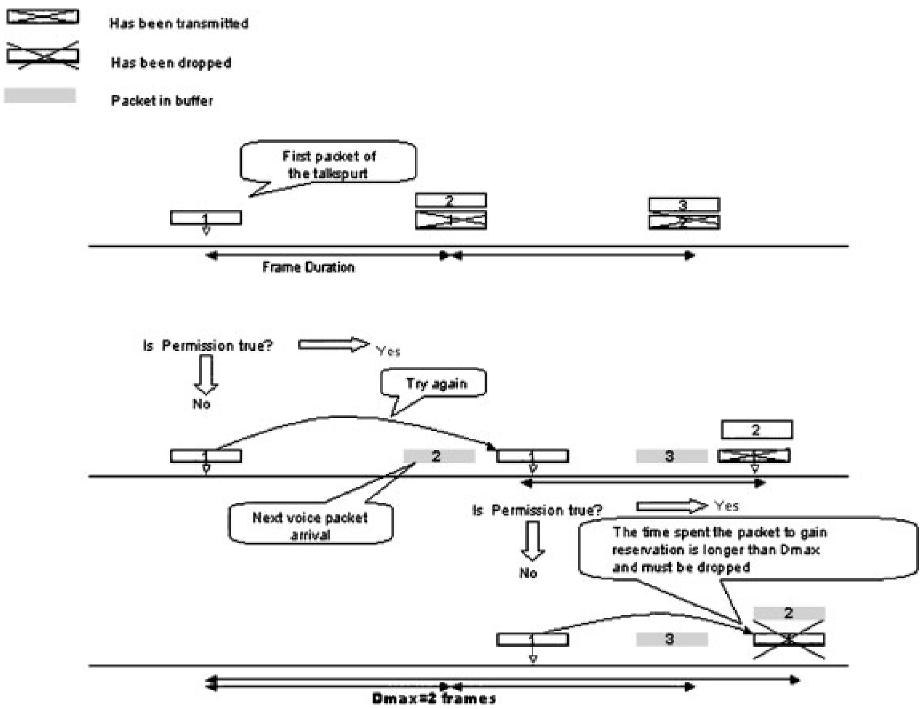

Fig. 2. Diagram of voice packets transmission.

Step 2: *Access Permission Probabilities for voice terminals*

```
IF NOCVP <>0
  IF (NOAC-NOCVP) <0
      Set voice probability as
      (NOAC/NOCVP)
  ELSE
      Set for voice probability
      the initial value
  END
ELSE
      Set for voice probability
      the initial value
END
```

Step 3: *Access Permission Probabilities for data terminals*

```
IF NOCDP <>0
      IF (NOAC-NOCVP) >0
             Set zero data
             probability
      ELSE
             Set data probability
             as (NOAC-NOCVP)/NOCDP
      END
ELSE
      Set for data probability
      the initial value
END
```

Essential parameters for voice and data initial probabilities have been taken from Reference [76] where the successful application of conventional PRMA protocol in LEO constellation has been proved.

For low load conditions it might be no contending voice or data packets. In this situation (NOCVP $= 0$, (NOAC-NOCVP)$> = 0$, NOCDP $=$ 0, NOAC-NOCVP) > 0) the proposed algorithm gives the 'initial probabilities' for voice and data, explained in the following.

4.5. The Case of MEO Satellite Systems

The proposed algorithm has a good performance in LEO constellation where the RTD is equal to the frame duration. The satellite can inform the user terminals about the channel status so they can have the ability to determine the permission probabilities, which are valid in a subsequent frame. In MEO constellation the RTD is much greater than in LEO. As a result a terminal is informed about the channel status with much greater delay. In such a situation more efficient ways to control the permission probabilities

Table I. Simulation parameters.

SIMULATION PARAMETERS			
CDMA channel rate	(R_c)	2048	(kbps)
PRMA channel rate	(R_p)	256	(kbps)
Spread factor	(SF)	8	
Frame duration	(T_f)	0.016	(sec)
Slot duration	(T_s)	0.001	(sec)
Slots per frame	(N)	16	
Voice Source rate	(R_s)	16	(kbps)
Maximum delay	($D_{\max}$)	0.032	(sec)
Input data traffic	(r_d)		variable
Message length	(L_b)		variable
Voice terminals			variable
Data terminals			variable
Permission probabilities	(P_{voice}, P_{data})		variable
Initial probabilities	(P_{invoice}, P_{indata})	0.6 0.2	

must be studied and this is an open topic for further work.

4.6. Simulation Results

A simulation tool has been developed in MODSIM III for the evaluation of the proposed scheme. Packets of length $L = 256$ bits have been chosen with a voice source rate of 16 kbps. The frame duration is equal to 16 ms. Thus the PRMA channel rate is equal to 256 kbps. Each frame consists of 16 slots of 0.001 ms duration. The CDMA channel rate R_c is 2048 kbps using a spreading factor equal to eight. The multiple access capability (Figure 1) is chosen equal to six, which means that the channel can support six simultaneous packet transmissions. Maximum delay for voice packets transmission, $D_{\max}$ has been chosen equal to 32 ms as in Reference [75] (two frame durations). Simulation parameters are shown in Table I.

For the data subsystem we denote by L_b the average message length in bits (information part). The corresponding average number of packets L_s can be obtained as described below, by assuming the same header size for voice and data packets.

$$L_s = \frac{L_b}{R_s T}[\text{packets/mess}] \quad (6)$$

The average input data traffic can be expressed as follows

$$r_d = \lambda T L_s N_d [\text{packets/slot}] \quad (7)$$

where λ is the Poisson mean rate of messages arrival.

The efficiency of the proposed work was measured through comparisons with the conventional PRMA, and the conventional CDMA/PRMA [77] where the

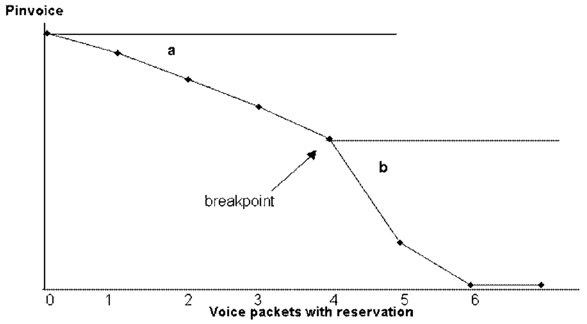

Fig. 3. Channel access function.

Channel Access Function (*caf*) control (for calculating the permission probabilities) has been introduced. For this *caf* essential parameters have been taken from Reference [78] and it is illustrated in Figure 3. The initial voice permission probability has been taken equal to $P_{\text{voice}} = 0.6$ where $a = 0.021$ and $b = 0.3$. For data terminals the permission probability has been taken equal to $P_{\text{data}} = 0.1^{*}P_{\text{voice}}$. In our work the initial permission probabilities for voice and data terminals have been taken equal to $P_{\text{voice}} = 0.6$ and $P_{\text{data}} = 0.2$ respectively.

4.7. Voice Transmission

Figure 4 depicts the variation of P_{loss} as a function of the number of simultaneous conversations. The proposed method is compared with the conventional PRMA and the conventional CDMA/PRMA and the improvement is obvious. This is due to the fact that the proposed algorithm counting the permission probabilities results in a better distribution of the packets in the slots without exceeding *mac*. Furthermore, as in Reference [78] reservation cancellations can be avoided by using the end-of-use flags so the number of dropped packets due to excessive MAI is reduced. We can see that the system can support at least 75 simultaneous conversations satisfying the voice quality ($P_{\text{loss}} < 1$ per cent). As it has been described above a voice retransmission mechanism (RM) has been also introduced in this work. In Reference [79] for voice terminals the trials for reservation are done in the same slot of subsequent frames because the frame and the voice arrival rates are equal. In our work (Figure 2) a voice terminal can try more than once until exceeding $D_{\max}$. Applying such a mechanism the performance of the system is definitely improved. From Figure 4, the bad performance of PRMA protocol in a heavy load channel can be noted. The performance is dramatically reduced when the number of simultaneous conversations is

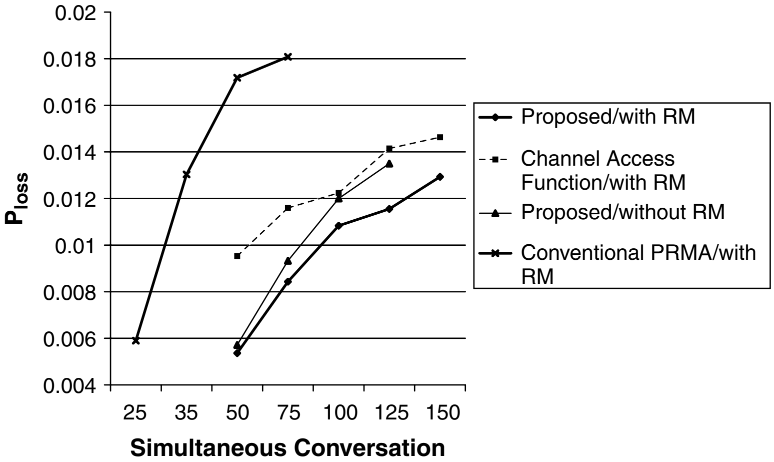

Fig. 4. P_{loss} as a function of simultaneous conversations in an LEO environment.

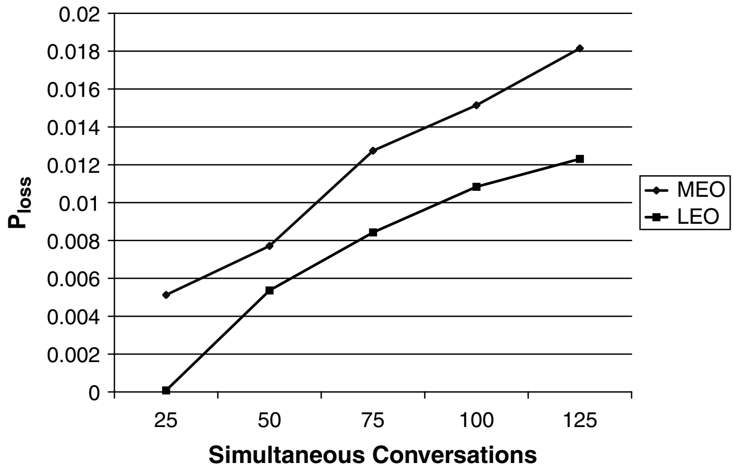

Fig. 5. P_{loss} as a function of simultaneous conversations in non-GEO constellations.

increased. As in Reference [76] the conventional PRMA can support a few voice terminals in a LEO environment.

In Figure 5 results for P_{loss} are also shown comparing the performance of the system for LEO and MEO constellations. It is obvious that the impact of the higher round trip is crucial for the performance of the system. As we can see, the performance of the CDMA/PRMA protocol in an MEO environment is reduced in heavy channel load, as the contention mechanism is getting harder.

4.8. Mixed Voice/Data Transmission

In Figure 6 P_{loss} as a function of simultaneous data transmissions is given. The results are compared with the conventional method after the application of the retransmission mechanism. It is obvious that increasing the number of data terminals reduces the quality of voice communications. The system can't support more than 80 simultaneous conversations when 30 data terminals share the same channel. The results are worse when we increase this number. Performance degradation is caused because the contention mechanism is getting harder. In each slot there are many candidates for reservation and since data terminals can reserve a slot in the same way with voice terminals, the number of dropped voice packets is increased. For the results in Figure 6 data messages with average message length equal to $L_b = 50$ kbp per message were considered with input data traffic equal to $r_d = 0.5$.

Finally, in Figure 7, results for data delay are shown for different data message length. As we can

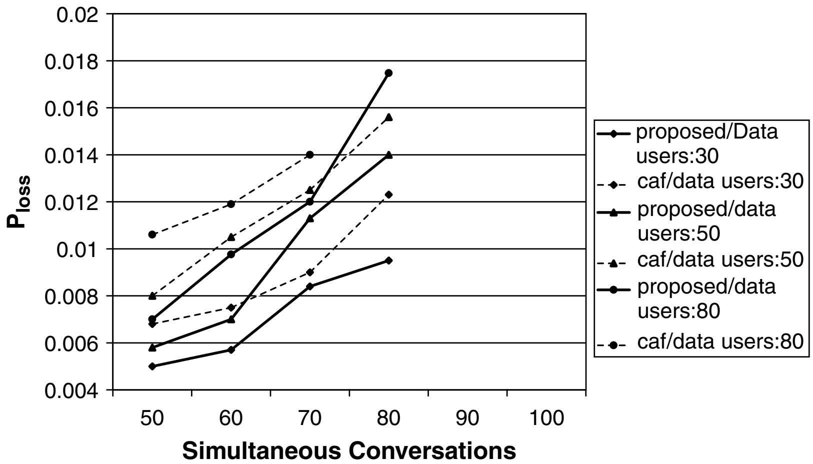

Fig. 6. P_{loss} as a function of simultaneous conversations in integrated Voice/Data transmission.

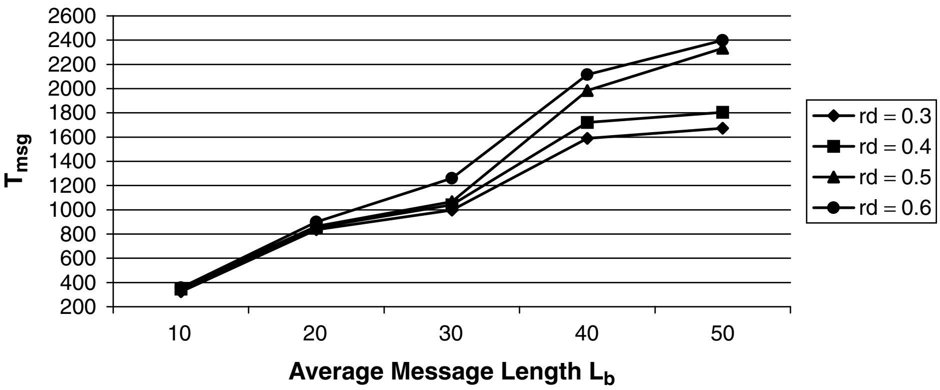

Fig. 7. T_{msg} as a function of average message length in different input data traffic.

see, by increasing the traffic rate more messages are produced in each terminal and the time to be served becomes longer. The contention mechanism is also harder and the time for a data reservation is longer, due to low permission probabilities. Increasing also the average message length it is obvious that the total message transmission is increased. In light load conditions the performance is almost the same because of the short length of messages. Short messages are served faster and they release the reservations before new messages arrive. For these simulations we use the same number of data and voice terminals (taken equal to 50).

5. Conclusions

The convergence and compatibility of both terrestrial and satellite networks are some of the main objectives of next-generation communication systems. In order for this to be achieved, satellites will play an important role due to their inherent characteristics. Therefore, new techniques must be developed to improve the existing satellite networks or new constellations must be established in order to fulfill user's demands for global mobility, coverage and multimedia services. There are numerous technical challenges that must be overcome in order to permit the successful and harmonious integration of satellite and terrestrial resources. In this paper some of the main issues of next-generation satellite networks have been addressed by giving emphasis in the MAC layer protocols. An adaptive CDMA/PRMA access technique was introduced, as a candidate for an uplink satellite channel, and from the results obtained, that it is very promising technique. Finally, research efforts on next-generation satellite networks, which have been taking place under the EU, have been mentioned.

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