High-Speed Satellite Mobile Communications: Technologies and Challenges

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Invited Paper

The central features of the future fourth-generation mobile communication systems are the provisioning of high-speed data transmissions (up to 1 Gb/s) and interactive multimedia services. For effective delivery of these services, the network must satisfy some stringent quality-of-service (QoS) metrics, defined typically in terms of maximum delay and/or minimum throughput performances. Mobile satellite systems will be fully integrated with the future terrestrial cellular systems, playing important roles as backbones or access satellites, to provide ubiquitous global coverage to diverse users. The challenges for future broadband satellite systems, therefore, lie in the proper deployments of state-of-the-art satellite technologies to ensure seamless integration of the satellite networks into the cellular systems and its QoS frameworks, while achieving, to the extent possible, efficient use of the precious satellite link resources. This paper presents an overview of the future high-speed satellite mobile communication systems, the technologies deployed or planned for deployments, and the challenges. Focusing in particular on the nonlinear downlink channel behavior as well as shadowing and multipath fading, various physical channel models for characterizing the mobile satellite systems are presented. The most prominent technologies used in the physical layer, such as coding and modulation schemes, multiple-access techniques, diversity combining, etc., are then discussed in the context of the satellite systems. High-speed and QoS-specific technologies, such as onboard processing and switching, mobility and resource managements, IP routing, and cross-layer designs, employed in the satellite systems are also discussed.

Keywords*—Adaptive modulation, channel modeling, cross-layer design, nonlinear amplifier, onboard processing, quality of service (QoS), resource management, satellite mobile communications.*

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I. Introduction

Satellite mobile communication has gained enormous attentions in the wake of third-generation (3G) and fourth-generation (4G) wireless communications systems and their challenges. The telecommunications industries are currently deploying the 3G system worldwide and researchers are coming up with new ideas for the next-generation wireless systems, as many challenges are yet to be fulfilled. These include high data rate transmissions (up to 1 Gb/s), multimedia communications, seamless global roaming, quality-of-service (QoS) management, high user capacity, integration and compatibility between 4G components, etc. To meet these challenges, researchers at present are focusing their attentions on the satellite domain by considering it as an integrated part of the so-called information superhighway [23], [30], [56], [80], [97], [137].

Satellite mobile systems are developed to provide connectivity between remote terrestrial networks, direct network access, Internet services using fixed or mobile terminals, interactive multimedia applications, and high data-rate transmissions. Most of these research and development scenarios have considered the nongeostationary satellite network for providing satellite-based mobile multimedia services because of its low propagation delay and low path loss [78].

As a result, new generations of broadband satellite communication systems are currently being developed to support multimedia and Internet-based applications. For example, the Spaceway system provides downlink transmission rates of up to 100 Mb/s, and a total capacity of up to 4.4 Gb/s. In order to significantly increase the capacity of 4G broadband satellite systems, current research aims at developing new advanced technologies. For example, efficiently employing 256-quadrature amplitude modulation (QAM) schemes in

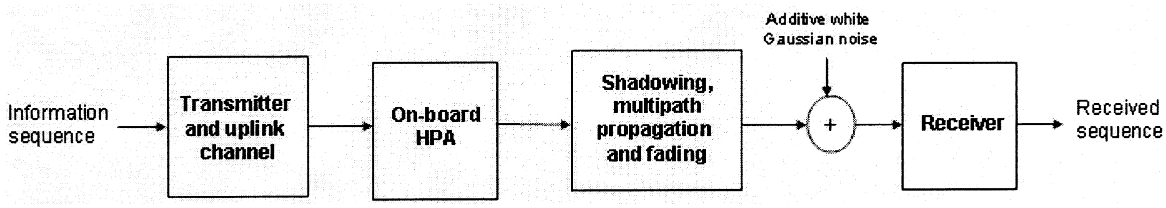


Fig. 1. Simplified base-band satellite mobile communication channel model.

the Spaceway system [instead of quadrature phase shift keying (QPSK) modulation], would lead to downlink transmission rates of up to 400 Mb/s and a total capacity of up to 17.6 Gb/s, for the same bandwidth occupancy as the one currently employed.

In this paper, we first present the main physical characteristics of the downlink satellite mobile channels. We focus in particular on the nonlinear channel behavior as well as shadowing and multipath fading. We then review the emerging technologies and approaches that aim to meet future challenges. These technologies include modulation schemes, predistortion and equalization, coding, multiple-access techniques, diversity combining, onboard processing, mobility and resource management, QoS provisioning, and cross layer design. We also review the key satellite mobile systems and their applications and services as well as the roles of satellites in the 4G systems. In this context, the focus is on the medium earth orbit (MEO), and/or low earth orbit (LEO) satellite networks. We also address the network and QoS issues. Throughout the paper, we discuss the challenges that have to be met in order to fulfill the 4G requirements.

The outline of this paper is as follows. Section II presents the physical satellite mobile characteristics. Section III discusses different technological advances and challenges. Section IV provides an overview of satellite mobile systems and discusses mobility and resource managements, QoS provisioning, IP routing, and cross-layer designs.

II. Physical Channel: Characteristics and Implications

To understand the technical difficulties and limitations of the satellite mobile communications systems, we need to know the physical channel characteristics. We will limit this section to the downlink, which requires much more resources than the uplink—mainly in terms of bandwidth, transmission rate, and power. This is because of the asymmetric nature of the traffics and applications between the two links. For example, satellite mobile systems providing high-speed Internet services allow users (through the downlink) to download multimedia data, which needs high capacity and high transmission rates. On the other hand, the uplink will require much smaller capacity and data rates as users will need to upload relatively small amounts of data—such as browsing requests, e-mail messages, basic user information (e.g., user ID and account code), etc.

References [96], [108], and [117] give detailed studies of satellite uplink and downlink budget analysis including the effects of the transmitting and receiving antennas and antenna and system noise as well as large-scale propagation. These references also discuss the overall signal-to-noise ratio (SNR) evaluation and the limitations caused by regulatory aspects and operational constraints. Several examples of end-to-end communication link budgets are given.

In this section we will focus on two major problems that highly affect the satellite mobile downlink performance. These are nonlinear distortions caused by onboard high-power amplifiers (HPAs) and shadowing and multipath fading. We will also present some analytical results on the combined effects of the amplifier's nonlinearity and the propagation channel in the satellite segment.

A. High-Power Amplifiers

In order to increase power efficiency, satellites are equipped with HPAs, such as traveling wave tube (TWT) amplifiers and solid-state power (SSP) amplifiers [9] (Fig. 1). HPAs have nonlinear transfer functions, which are characterized by amplitude conversion (AM/AM) and phase conversion (AM/PM). Equations (2.1) and (2.2) give an example of a typical TWT model used in satellite communications, where $A(.)$ and $\Phi(.)$ are the AM/AM and AM/PM conversions, respectively [9], [96], [125]:

$$A(r) = \frac{2r}{1+r^2} \tag{2.1}$$

and

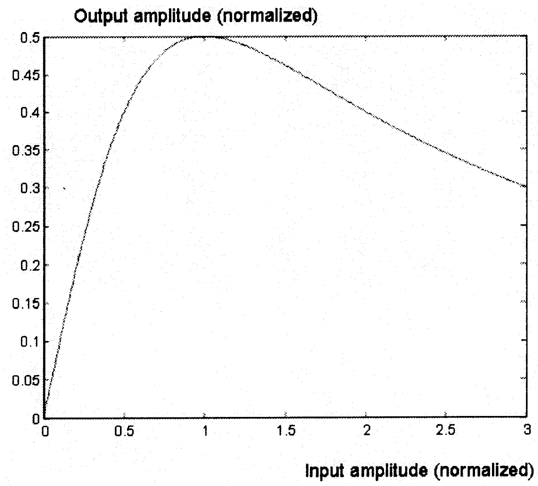
$$\Phi(r) = \frac{r^2}{1+r^2} \tag{2.2}$$

where r is the amplifier input signal amplitude. Fig. 2(a) and (b) illustrate the nonlinear behavior of the amplitude and phase conversions, respectively.

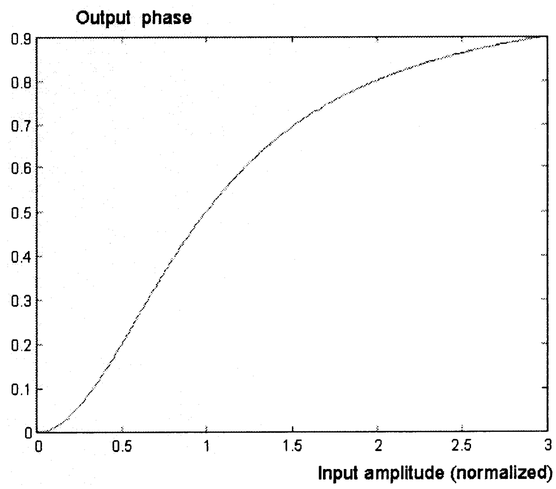
The amplifier input backoff (IBO) is defined as the ratio between the amplifier input saturation power (P_{sat}) to the input signal power (P_{in})

$$IBO(dB) = 10\log\left(\frac{P_{\text{sat}}}{P_{\text{in}}}\right).$$

The HPA nonlinear transfer function causes severe nonlinear distortions to the input signal, especially when the HPA is operated near its saturation region (i.e., for maximal power efficiency). The distortions are particularly important when multilevel modulation schemes are employed, such as M-array quadrature amplitude modulation (M-QAM) ($M > 4$) [9], [16]. This is illustrated in Fig. 3 where a rectangular 64-QAM signal [Fig. 3(a)] is transmitted through a nonlinear channel. In this case, the output constellation



(a)



(b)

Fig. 2. (a) HPA amplitude conversion (b) HPA phase conversion.

(Fig. 3(b)] is severely distorted. This results in a significant degradation of the satellite channel symbol error rate (SER) performance. Because of this nonlinear problem, early satellite systems have been restricted to simple (and, therefore, spectrally inefficient) modulation schemes, such as binary phase shift keying (BPSK) modulation, which are less sensitive to the nonlinear problem than spectrally efficient modulation schemes. In order to achieve high data rates and low bit error rates (BERs) (which are among the requirements of 3G and 4G mobile communication systems), significant research efforts are being carried out at the industrial and academic levels to allow the use of spectrally efficient modulation schemes in a nonlinear environment. Section III presents an overview of these techniques.

B. *Multipath Propagation and Fading*

The movements of satellites and mobile terminals cause the radio propagation channel to have a random and time-varying behavior. Significant amounts of research have been carried out in the last two decades on satellite mobile channel measurement and modeling [88]. For example, in the framework of the Canadian mobile satellite (MSAT) program, the Communication Research Centre (CRC) has developed a propagation measurement program for land mobile satellite channels. The objective of the program was to provide engineering design data on excess path loss, covering suburban and rural areas. Measurements were carried out at both the ultrahigh frequency (UHF) (800 MHz) band and the L-band (1542 MHz). In Europe, the German Aerospace Research performed a series of propagation measurements in the L-band in several European cities. The National Aeronautics and Space Administration (NASA) has also performed an extensive measurement work on the L-, S-, and Ka- (20- to 30-GHz) bands. The Ka- band studies are of a particular interest for gigabit data transmissions and multimedia applications and services. A number of propagation measurements have been made in the Ka- band used Italsat, ACTS (NASA's Advanced Communications Technology Satellite), and Olympus [12], [88], [89], [92], [93], [101], [114].

For the purpose of satellite system analysis, design, and simulation, mathematical models for the land mobile satellite channel are needed. Extensive research works have, therefore, been carried out to develop measurements-based statistical models [12], [88], [89], [92], [93], [101], [114], that are particularly suitable for Ka- band and higher frequencies. For example, the authors in [31] give a comprehensive survey of the most accepted statistical models proposed in the scientific literature, considering large-scale and small-fading, single and multiple-state structures, narrowband and wideband channels, and first- and second-order statistics. Building upon a thorough characterization of propagation effects, the authors focus on performance analysis of coded and uncoded systems based on closed-form expressions, upper bounds, and numerical simulations. An excellent survey of modeling and estimation of various mobile channels is presented in [138]. Channel modeling is followed by a discussion on various approaches to channel estimation including training-based approaches, semiblind approaches, and hidden pilot-based approaches.

Since the Ka- band (20–30 GHz) is found to be the most appropriate frequency band for multimedia and IP applications with very high data rates, we will first present our discussion on the Ka- band models, where we will consider Loo's [88]–[92] model. Later, we will discuss multistate statistical channel models, which have recently been given considerable attention.

1) Loo's Channel Model: For the Ka- band models we will focus on Loo's models [88]–[92], which present simple and accurate probability density functions (pdf's) for the envelope and phase. These pdf's have been shown to depend on the weather conditions.

For a fixed satellite channel, the signal envelope and phase can be modeled as Gaussian, and their expressions are given by [88]

$$p_w(r) = \frac{1}{\sqrt{2\pi}\sigma_w} \exp\left[-\frac{(r-m_w)^2}{2\sigma_w^2}\right] \tag{2.3}$$

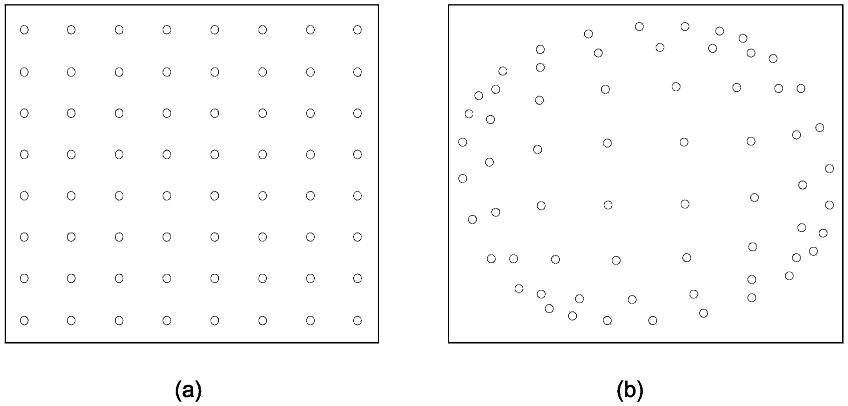


Fig. 3. Effect of HPA nonlinearity on a 64-QAM constellation. (a) Transmitted constellation before amplification. (b) Constellation at the HPA output.

Table 1
PDF Parameters for Different Weather Conditions [88]

Weather condition	m_w	σ_w	m_{w0}	σ_{w0}
Clear sky	0.413	0.00087	0.0072	0.00357
Rain	0.662	0.02	-0.0089	0.03077

and

$$p_w(\phi) = \frac{1}{\sqrt{2\pi}\sigma_{w0}} \exp\left[-\frac{(\phi - m_{w0})^2}{2\sigma_{w0}^2}\right] \tag{2.4}$$

where m_w, σ_w and m_{w0}, σ_{w0} are the mean and variance of the envelope and phase, respectively.

Examples of these parameters are given in Table 1.

For the satellite mobile channel, the model assumes that the line-of-sight (LOS) component under shadowing is log-normally distributed, and that the multipath effect is Rayleigh distributed. The signal is then the sum of a log-normal variable z, and a Rayleigh variable w[88]–[92]

$$r \exp(j\theta) = z \exp(j\phi_0) + w \exp(j\phi) \tag{2.5}$$

where z is a variable with a log-normal probability distribution (corresponding to shadowing) having standard deviation $\sqrt{d_0}$ and mean μ, and w is a Rayleigh distributed variable (corresponding to multipath fading).

The signal envelope pdf was shown to be given by [88], [90]

$$\begin{aligned} p(r) &= \frac{r}{b_0\sqrt{2\pi d_0}} \\ &\cdot \int_0^{+\infty} \frac{1}{z} \exp\left[-\frac{(\ln z - \mu)^2}{2d_0} - \frac{(r^2+z^2)}{2b_0}\right] \times I_0\left(\frac{rz}{b_0}\right) dz, \end{aligned} \tag{2.6}$$

where b_0 represents the average scattered power due to multipath (Rayleigh fading) and $I_0(.)$ is the modified Bessel function of zeroth order.

It is clear from (2.5) [88], [90] that when z is a constant (i.e., the LOS is directly received with no shadowing), the signal envelope follows a Ricean distribution

$$p(r) = \frac{r}{b_0} \exp\left[-\frac{(r^2 + A^2)}{2b_0}\right] \times I_0\left(\frac{rA}{b_0}\right). \tag{2.7}$$

In the case where there is shadowing z, but no multipath fading, i.e., $w = 0$, the envelope pdf is log-normal, and is given by

$$p(r) = \frac{1}{r\sqrt{2\pi d_0}} \exp\left[-\frac{(\ln r - \mu)^2}{2d_0}\right]. \tag{2.8}$$

In the case where there is no shadowing and no LOS (i.e., $z = 0$), the signal envelope pdf is Rayleigh distributed

$$p(r) = \frac{r}{b_0} \exp\left(-\frac{r^2}{2b_0}\right). \tag{2.9}$$

The signal envelope pdf allows calculating the shadow margins in the design of the communication system [132]. This calculated shadow margin is used for handoff and power control purposes. The pdf also allows the estimation of the level crossing rate (LCR) and average fade duration (AFD). These two parameters are important for the choice and design of the modulation, coding, and equalization techniques. They are also key parameters for emerging signal processing technologies, such as adaptive modulation and multiple-input multiple-output (MIMO) techniques [72].

For the signal phase model, ϕ has been shown to follow a Gaussian distribution

$$p(\phi) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\phi - m)^2}{2\sigma^2}\right]. \tag{2.10}$$

Studies [88]–[90] have shown that, for the Ka- band, one should take the weather conditions into account, in addition to fading and shadowing. Since the two processes can be considered as being independent, then the combined signal envelope pdf is given by

$$p_T(r) = p_w(r) \times p(r) \tag{2.11}$$

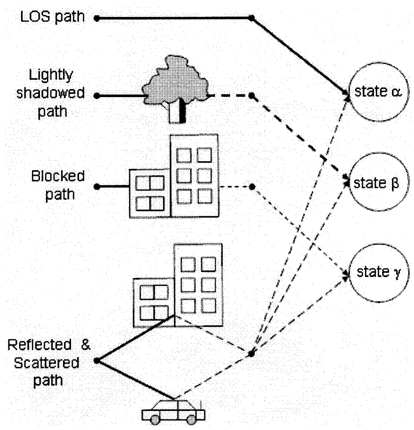


Fig. 4. Three-state statistical channel model.

where $p_w(r)$ and $p(r)$ are given by (2.3) and (2.6), respectively.

The resulting phase pdf is Gaussian

$$p_T(\phi) = p(\phi_w + \phi_s) \tag{2.12}$$

where ϕ_w and ϕ_s are the phases caused by weather conditions, and shadowing and fading, respectively.

2) Multistate Statistical Models: These models are introduced, especially for the nongeostationary link of the satellite channels, to represent the variations in the statistical nature of the channel that arise from the change in the elevation angle and from the mobility of the satellite terminals between different environments. The Markov process, which requires the state probability array and the state transition probability matrix, provides the basis of these models. Based on the characteristics of different geographical locations, different researchers have come up with different multistate models. Here we will discuss some of these models.

In [83], the authors proposed a three-state model as shown in Fig. 4. Here, state α is represented by the Rice distribution due to the presence of LOS components, state β is represented by Loo's distribution due to the presence of a shadowed direct component along with a Rayleigh distributed component, while state γ is represented by Rayleigh distribution due to the presence of complete blockage of the direct path. As a result, the total pdf provides a weighed linear combination of Rice, Loo and Rayleigh distribution, which becomes

$$p(r) = a_1 p_{\mathrm{Rice}}(r) + a_2 p_{\mathrm{Loo}}(r) + a_3 p_{\mathrm{Rayleigh}}(r) \tag{2.13}$$

where a_1, a_2 and a_3 are the weighting factors, which are determined in terms of the characteristics of the experimental environment. Similar models were proposed in [59] and [60]. It is interesting to note that, with $a_3 = 0$, (2.13) reduces to the two-state model proposed by Barts *et al.* [8].

Wakana [149] proposed a two-state-based model. This two-state model with *fade* and *nonfade* states is represented through a five-state Markov process as shown in Fig. 5, where p_1, p_2, q_1, q_2, and q_3 represent different state-transition probabilities. In this case, two fade states, fade a and b, correspond respectively to short and long fade states

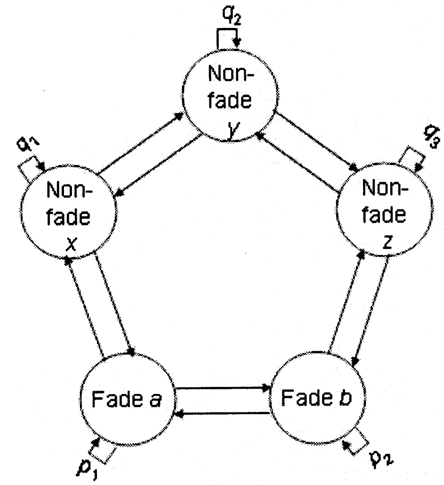


Fig. 5. Five-state Markov process.

while three nonfade states (nonfade x, y, z) correspond to nonfade states having short, long and very long durations, respectively.

Based on the measurements, over European areas at elevation angles in the range of 13° to 43°, the authors in [93] introduced a two-state model identified as *good* and *bad* states. In this case, the good channel state represents the LOS components while the bad channel state represents the shadowed components from the satellite. In the good state, the overall received envelope follows Rice distribution whereas in the bad state, the distribution is conditionally Rayleigh with mean power varying according to lognormal distribution, due to shadowing. The important parameter of this model is the shadowing time-share Q, which determines the probability to be in either good or bad state. With the instantaneous received power S, the pdf of this model is given by

$$p(S) = (1-Q)\, p_{\mathrm{Rice}}(S) + Q \cdot \int_0^\infty p_{\mathrm{Rayleigh}}(S|S_I) p_{\mathrm{Lognormal}}(S_I)\, dS_I \tag{2.14}$$

where S_I is the instantaneous shadowing power variable and $p_{\mathrm{Lognormal}}$ is the corresponding lognormal distribution. By replacing the LOS component amplitude in the good state with a binomial distribution, Rice *et al.* [115] proposed a variation on the model presented in [93]. The interested readers can also see [147] for a general M-state model.

3) Channel Modeling Challenges: One fundamental characteristic of future satellite mobile communication systems is the necessity to be fully integrated into the other terrestrial networks in order to enable global, seamless, and ubiquitous communications. With emerging nongeostationary LEO and MEO satellite systems and high data rate applications, accurate and flexible channel models are needed in order to allow realistic QoS predictions and perform system comparisons under different multiple-access, modulation, coding and diversity schemes. For future satellite mobile systems, a suitable channel model should satisfy the following characteristics: the model should be based on accurate estimation and modeling of propagation statistics, the model should combine very well the effects of weather attenuation process and the multipath fading and shadowing process, and the model should consider the different channel state changes, for example, from a shadowing to a nonshadowing state or vice versa. The choice of channel modeling and estimation should take into account the computational complexity and implementation issues for real-time processing. It should also be tightly linked to its use in performance prediction and system optimization [31]. As we will see in the following sections, efficient channel modeling and estimation is very important for emerging techniques, such as adaptive signal processing, adaptive coded modulation, and cross-layer design [6], [71]. Future research directions will include the exploitation of new frequency bands to accommodate increasingly high data rates, which will necessitate exploring new channel models.

III. Physical Layer Technologies and Challenges

This section reviews the most important technologies used for high-speed satellite mobile communications. We review in particular: Modulation and coding aspects, multiple-access techniques, diversity combining, performance evaluation. Here we also address different challenges for each technology.

A. Modulation in the Light of Spectral and Power Efficiency

Spectral efficiency demonstrates the ability of a system (e.g., modulation scheme) to accommodate data within an allocated bandwidth while power efficiency represents the ability of a system to reliably transmit information at a lowest possible practical power level. Joint optimization of spectral and power efficiency parameters is a very challenging task. In addressing this challenge, we focus on different modulation and coding techniques, with the objective that an intelligent use of these two techniques can significantly improve both parameters, somewhat simultaneously. In this section, we will discuss different modulation techniques, which are already in use in the 3G systems and/or are being addressed for 4G seamless systems.

1) Different Modulation Schemes, Currently in Use: The deployed 3G mobile communications systems use different variants of phase shift keying (PSK) and QAM modulation techniques for achieving high spectral and, to some extent, high power efficiencies. The first group (PSK) is also in use in the satellite domain (e.g., see [17]). On the other hand, for very high bit rate applications, multicarrier modulation, also known as orthogonal frequency division multiplexing (OFDM), is being addressed [106] in satellite mobile communications. In this section, therefore, we will focus on these three types of modulation techniques.

a) PSK Modulation: In this type of digital modulation technique the modulating data signals shift the phase of the constant amplitude carrier signal between M number of phase angles ($M = 2$ for BPSK and $M = 4$ for QPSK). Due to their simplified form, reasonable power, and spectral efficiencies, and immunity to noise and interference, BPSK and QPSK modulation techniques are used mostly for satellite links. The example includes Iridium (a voice/data satellite system) and Digital Video Broadcasting Satellite (DVB-S) systems. Besides, in both IS95 and CDMA2000[1] (also known as 3G IS-2000) cellular systems BPSK/QPSK and OQPSK modulation techniques are used in the forward and reverse links respectively. 8PSK finds its application in enhanced data rate for GSM evolution (EDGE) cellular technology. $\pi/4$ DQPSK modulation is used, for IS54 [North American Digital Cellular (NADC) system] and cordless personal communications services in North America, for Pacific Digital Cellular (PDC) services [113] in Japan, and for Trans-European Trunked Radio (TETRA) systems in Europe. In 3G cellular data-only system (IS856, also known as cdma2000 1xEV-DO), BPSK modulation is used in the reverse link while QPSK and 8QPSK modulations along with QAM techniques are used in the forward link to support multirate data applications.

b) QAM: QAM is simply a combination of pulse amplitude modulation (PAM) and PSK modulation techniques. In this modulation scheme, two orthogonal carrier frequencies (in-phase and quadrature carriers), occupying identical frequency bands, are used to transmit data over a given physical channel. By choosing different amplitudes and phases, different constellations of QAM signals can be formed [109]. In this case, the power efficiency of the communication system will vary depending on the type of signal constellation [62] used for the QAM technique. Due to the flexibility of using different amplitudes and phases, even with higher levels ($M > 4$), the choice of decision region in QAM is not as critical as PSK. Moreover, QAM modulation offers an additional flexibility concerning the shape of the constellation: for a given number of symbols, different constellations can be formed, yielding different performance results.

QAM is used in applications including microwave digital radio, DVB-C (Digital Video Broadcasting-Cable) and modems. In the 3G cellular data-only system (IS856), 16-QAM technique, along with QPSK and 8QPSK modulations, is used in the forward link to support multirate data applications. These days, QAM is getting enormous attention in satellite communications due to its spectral and power efficiencies [107].

c) OFDM: OFDM is a wideband modulation scheme, which is specifically designed to cope with the problems of multipath reception. It achieves this by transmitting a large number of narrowband digital signals over a wide bandwidth. In OFDM, the data is divided among a large number of closely spaced orthogonal carriers which results high spectral efficiency. Moreover, only a small amount of data is carried on each carrier, and this significantly reduces the influence of *intersymbol interference* (ISI) [129]. In this case, the parallel transmission provides the capability of supporting high bit rate applications. OFDM signals can easily be transmitted and received using the fast Fourier transform (FFT) devices [26], [103] without increasing the transmitter and receiver complexities. However, the scheme

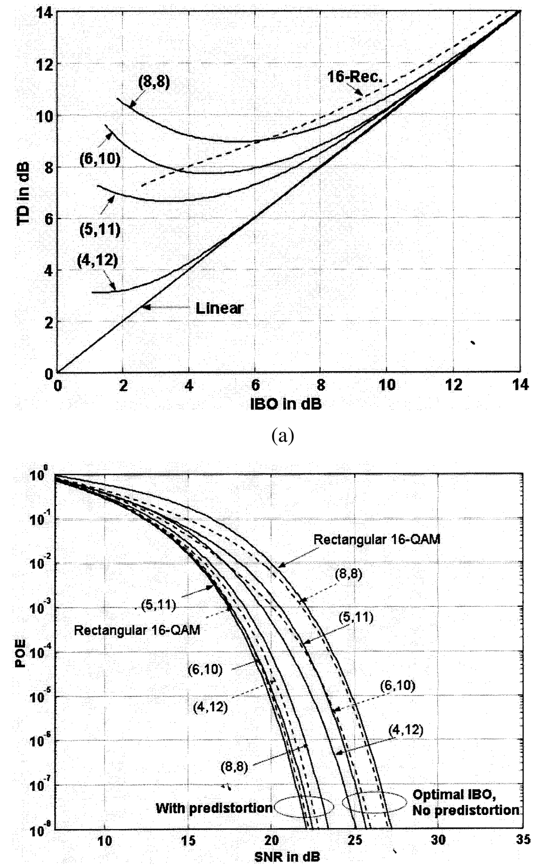
[1]http://www.qualcomm.com/cdma/3g.html

has some disadvantages too. It has a large peak-to-average power ratio (PAPR), which reduces the power efficiency and increases the cost of the power consumption of the transmitting amplifier. Moreover, OFDM techniques are susceptible to frequency offset and phase noise. Coding methods have been proposed in [27] and [57] to reduce the peak-to-average power ratio.

The use of OFDM technique finds its commercial wired applications in the digital subscriber line (DSL) [25], [130]. In the wireless system, OFDM is the main basis for several television and radio broadcast applications, including the European digital audio broadcasting (DAB) and high-definition TV (HDTV) terrestrial broadcasting [51], [52], as well as North American digital radio broadcasting. By the beginning of the 21st century, OFDM has been adopted as a standard for new high-rate wireless local area network (WLAN), such as IEEE 802.11, HIPERLAN II, as well as the Japanese Multimedia Mobile Access Communications (MMAC) [102]. Currently, many researches are underway to devolve an OFDM-based system to deliver mobile broadband data service at data rates comparable to those of wired services, such as DSL and cable modems. Moreover, OFDM technology is a very attractive candidate when targeting high quality and high flexibility in mobile multimedia communications over satellite systems [57].

2) Challenges in Next-Generation System Concerning Different Modulation Techniques: In the 4G system, there are many challenges to be addressed, some of which are leftovers from the deployed 3G system. Now that researchers visualize the 4G communication system as a single entity, consisting of both the satellite and terrestrial domains, some of the challenges related to modulation issue in the satellite domain, especially in the down link, need be tackled. At the signal processing level, extensive work is being done worldwide in order to meet the challenges of spectral and power efficiency in a fading and/or nonlinear environment [72].

As shown in [34], [107], and [110], among the spectrally efficient modulation schemes, M-QAM offers the best tradeoff between implementation complexity and performance in the nonlinear channels. Consequently, for the satellite channel where both spectral and power efficiencies are prime requirements, QAM becomes a strong candidate for the 4G mobile communications systems. The main challenge here is to come up with an optimal constellation for the QAM technique both in terms of BER performance and complexity. Moreover, for multimedia applications where the desired bit rate is in the gigabit range, the integration of OFDM technique with the QAM scheme will be another interesting challenge. Some of these challenges are already in the research phase [4], [14], [111], [156], which shows some remarkable results. In [4] and [5], performance analysis of a 16-QAM and 32-QAM-based nonlinear additive white Gaussian noise (AWGN) satellite systems over AWGN channels using different constellations have been presented in terms of probability of error (POE). For the nonlinear amplifier, the traveling wave tube amplifier (TWTA) has been used in this investigation. The analytical models,



(a)

(b)

Fig. 6. (a) Total degradation performance for different 16-QAM circular constellations in the presence of a nonlinear amplifier. (b) Performance of different 16-QAM circular constellations in the presence of a nonlinear amplifier, with and without predistortion.

presented for different constellations, provide the means to calculate the optimum ring ratio and phase difference for the best possible POE. For example, Fig. 6(a) shows the analytical POE performance of 16-symbol constellations such as rectangular 16-QAM, (8,8) and (5,11) constellations in terms of total degradation in the presence of nonlinearity. The total degradation, *TD*, is defined as the sum of the amplifier IBO and the increment Δ in the SNR required to maintain a given SER (which is taken here equal to 10^{-4}) with respect to the linear channel case. For each constellation, the figure shows the optimal IBO that delivers the lowest total degradation. Data predistorter can considerably mitigate the amplifier nonlinear effects by mapping the input constellation in such a way that at the output of the nonlinear HPA, it can compensate the amplitude compression and phase rotation introduced by the HPA. The analytical results [Fig. 6(b)] show significant improvement [e.g., 8.54 dB for star (8,8) constellation] of the POE performance when data predistortion is employed, compared to the nonpredistoted case for which optimal IBO is used. Readers can refer to [5], [9], [14], [38], [71], and [82] for other predistortion techniques such as neural network, polynomial, and Volterra series-based predistorters.

An interesting signal processing approach for the modulation scheme, known as the adaptive modulation technique

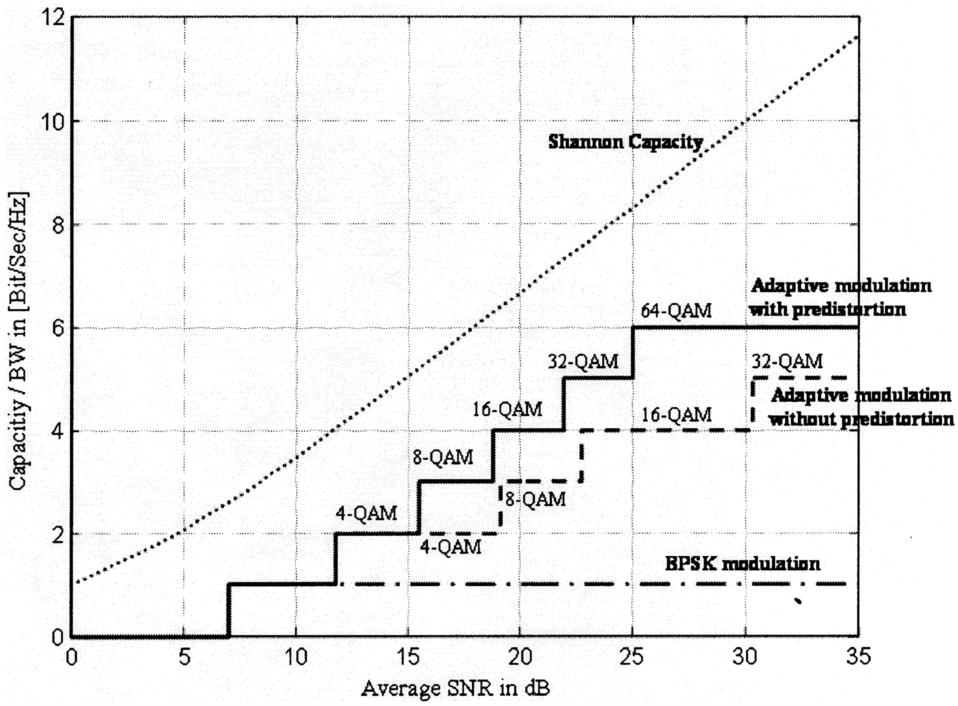


Fig. 7. Channel capacity when adaptive modulation and data predistortion are employed, comparison to adaptive modulation without predistortion, and nonadaptive BPSK scheme.

[3], [66], is currently being considered in the satellite domain due to its high throughput capability. This technique allows adapting the modulation schemes of interest (e.g., M-QAM constellation) to the current channel conditions (e.g., SNR level, fading characteristics, amplifier backoff, etc.) and, thus, may improve the channel capacity, power, and spectral efficiencies of the system. To reduce the nonlinear distortions as well as intersymbol interferences (which are caused by frequency selective fading [113], [132] and by the different filters present in the satellite system, as well as by the HPA spectral regrowth [9]), efficient equalization techniques are also carried out. In this case, the most popular techniques are based on linear adaptive filtering [109], Volterra series [9], and neural network equalizers [71], [73]–[76], [157]. These results need to be extended considering OFDM technique because the effectiveness of the predistorters with multiple carriers is still unknown. In this area, an investigation presented in [119] analyzes the error probability performance of nonlinearly distorted OFDM signals, considering coding strategy. Fig. 7 illustrates the improvement in the channel capacity when adaptive modulation is employed, with or without data predistortion. In [3], with the aid of adaptive modulated scheme, the authors have shown that, for variable-power variable-rate (*vpvr*) adaptation case, the spectral efficiency for an MQAM system in a Rayleigh fading channel can be equated as

$$\frac{\langle C\rangle_{\mathrm{vpvr}}}{W} = \int_{\gamma_0}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0}\right) p_\gamma(\gamma)\, d\gamma \tag{3.1}$$

where $\langle C\rangle_{\mathrm{vpvr}}$ represents the capacity in terms of bits per second for variable-power variable-rate adaptation, W represents the signal bandwidth in hertz, γ_0 is the optimal cutoff SNR-level below which data transmission gets suspended and $p_\gamma(\gamma)$ is the pdf of the received SNR γ. In [3], it has been shown that to apply the expression of (3.1), the following equality needs to be satisfied:

$$\int_{\gamma_0}^{\infty} \log_2\left(\frac{1}{\gamma_0} - \frac{1}{\gamma}\right) p_\gamma(\gamma)\, d\gamma = 1. \tag{3.2}$$

For the constant power-variable rate (*cpvr*) adaptation case, the expression for the spectral efficiency was shown to be [3]

$$\frac{\langle C\rangle_{\mathrm{cpvr}}}{W} = \int_{0}^{\infty} \log_2(1+\gamma) p_\gamma(\gamma)\, d\gamma. \tag{3.3}$$

Using (3.1) it can be shown through Fig. 8 that with a target BER of 10^{-6} in the Rayleigh fading channel, MQAM adaptive modulation scheme can provide about 40-dB power gain over nonadaptive counterpart. Moreover, it is observed that, this uncoded scheme provides about 11-dB power difference, at a spectral efficiency of 2 b/Hz and higher, when compared to Shannon capacity limit. These results suggest that the use of adaptive modulation technique would be a challenging area to explore in the satellite domain.

Besides all the challenging issues discussed above, carrier acquisition and tracking of the incoming signal, that makes coherent detection possible in the receiver, provides another challenging scenario, especially in the presence of high data rate environment. As a solution to this problem, differential modulation technique (such as DQPSK) can be used with differential detection. However, this scheme suffers from performance degradation compared to ideal coherent detection. For a power limited system (such as a satellite with onboard power amplifier), this degradation cannot be tolerated. Multiple-symbol differential detection [44] can be used to avoid

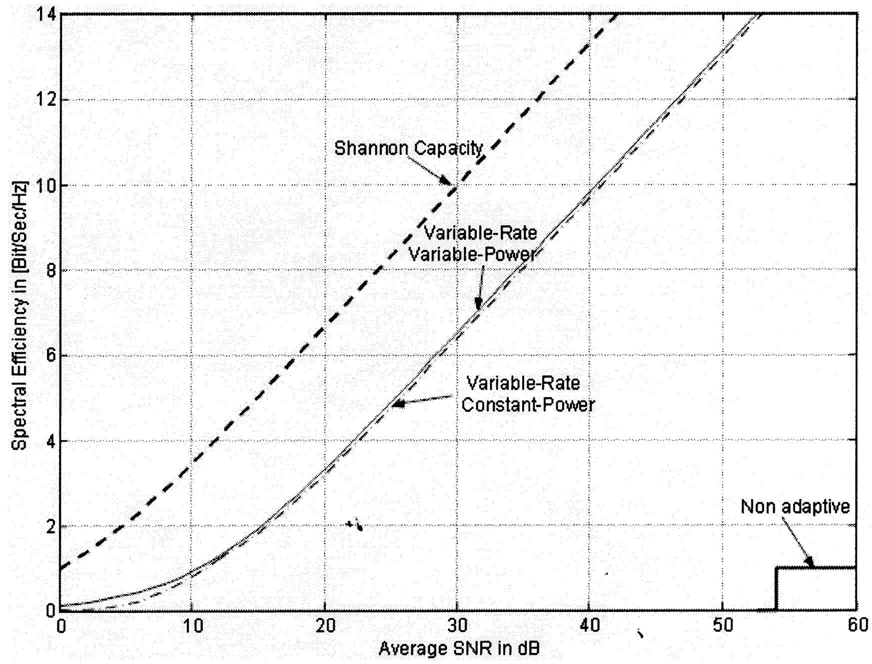


Fig. 8. Spectral-efficiency comparison between adaptive and nonadaptive QAM systems in Rayleigh fading channel with target BER $= 10^{-6}$.

this degradation by slightly increasing the length of the observation interval. All the above-mentioned studies need be extended to the fading channel scenario.

B. Coding

In this section we will discuss the channel coding aspects of next-generation mobile communications systems. Channel coding is applied to ensure adequate transmission quality of the signals. It is a systematic approach for the replacement of the original information symbol sequence by a sequence of code symbols, in such a way as to permit its reconstruction. Channel coding can improve the severe transmission conditions in terrestrial mobile radio communications due to multipath fading. On the other hand, it can help to overcome very low SNR for satellite communications due to limited transmit power in the downlink. In general, channel coding improves the power efficiency of a transmission scheme at the expense of spectral efficiency. It is interesting to note that in general the coded modulation technique can improve both power and spectral efficiencies of the communications system.

1) Recently Addressed Coding Techniques in the Research: The coding techniques being discussed in the recent trend of mobile and satellite communications systems include linear block codes [e.g., Hamming Codes, BCH codes, Reed–Solomon Codes (RS), etc.] and convolutional codes. On the other hand, the Turbo code (TC) technique is getting enormous attention in the current developments of both 3G and 4G telecommunications systems [16]. Moreover, to provide improvement in power efficiency without sacrificing the bandwidth efficiency, different coded modulation schemes, namely, trellis coded modulation (TrCM) [139], [140] and Turbo coded modulation (TCM) [47], [148], [116] are getting good attention.

In [124], to avoid high degree of complexity in Viterbi decoding, the authors use concatenated codes based on multilevel coded modulation (MCM). In this case, the outer RS code is concatenated with an MCM for high data rate application over satellite channels. The results show a significant coding gain in terms of BER with considerably less complexity. In [136], the authors have used RS code with interleaving for the lognormal shadowed Ricean fading satellite channel. The results show that there is a tradeoff between the coded block length and degree of interleaving. It is found that by carefully employing RS codes, the fade margins in the channel can be reduced up to 10 dB. Block turbo codes (BTC) with trellis-based decoding are proposed in [143] for asynchronous transfer mode (ATM) transmission in digital video broadcasting-return-channel via satellite.

To achieve better spectral and power efficiencies along with higher throughput (b/s/Hz), all the aforementioned coding techniques, combined with adaptive modulation schemes, are being addressed recently. In [133] an adaptive coding and modulating transmission scheme for 3G mobile satellite systems is proposed. Here the adaptation mechanism is based on the Rice factor of the channel, which is estimated in real time using an estimation algorithm at the receiver. The transmitter, upon receiving the channel information from the receiver, determines the optimal coding and modulation scheme using a lookup table. For coding scheme the authors use convolutional coding of rate $\frac{1}{2}$ and $\frac{1}{3}$ while for modulation scheme QPSK and 8PSK modulation formats are used. The simulation results in the satellite–universal mobile telecommunication system (S-UMTS) environment show that the dynamic range of the transmission power is greatly reduced, which, in turn, eases the power control requirements. In [67], the authors have employed adaptive TrCM in Rayleigh fading channel

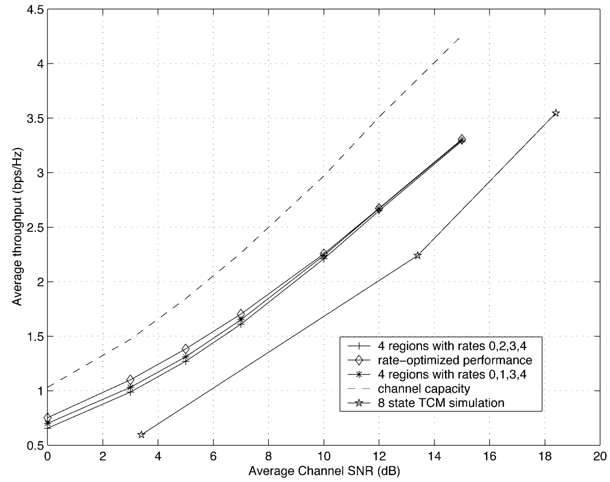


Fig. 9. Spectral efficiency of different states of an adaptive TCM scheme in Rayleigh fading channel [144].

in the presence of different code states, where it has been shown that the resulting scheme can get as close to 6-dB power difference (constant BER of 10^{-6}) when compared to Shannon capacity limit. This power difference was shown to be 3 dB only when the authors in [144] considered the same scenario in the presence of adaptive TCM (Fig. 9).

Besides, all the above research outputs, many investigations are in progress considering coding in the combined satellite and terrestrial area. Instead of discussing all these approaches and results, next we consider the challenges that some of the above-mentioned works have laid forth in the next-generation system.

2) Coding Challenges in the Next-Generation System: Now that the 3G system is already in use somewhat successfully in the terrestrial domain, current attention in the coding challenges is focused mainly in the satellite domain for the 4G system. In designing 4G mobile satellite systems, transmitted power is a critical issue. Adaptive coded modulation technique in [133] is already shown to be a smart solution to address this challenge. But the performance of the scheme is dependent on perfect estimation of the channel state information (CSI), which becomes a challenging task in the mobile satellite domain where the sources and destinations are far apart. Moreover, while working with adaptive modulation schemes, power efficiency for certain modulation techniques (e.g., MPSK) cannot be achieved without sacrificing spectral efficiency. In this situation, the use of coded QAM technique with adaptation between different QAM constellations could be a good choice to gain both power and spectral efficiencies. The application of adaptive OFDM technique with coding can also be explored in this situation upon successfully addressing the demerits of the OFDM method discussed earlier.

C. Multiple-Access Techniques

In a satellite multimedia system, designing a multiple-access scheme (MAS) is one of the most challenging issues [78]. The MAS is expected to provide the means for several terrestrial users to simultaneously access a satellite terminal efficiently. Over the last three decades, MASs have been proposed and studied, each adapted to satisfy the needs of specific system and to provide optimum performance under certain conditions. When the research interest is in the integration process of 3G terrestrial systems with the satellite domain, the conventional frequency division MAS (FDMA) system looses its flavor in competing with the code division MAS (CDMA) and time division MAS (TDMA)-based systems for its very high bandwidth (BW) requirement. Moreover, in satellite systems, it is shown [61] that CDMA system outperforms the FDMA system when diversity is taken in to account. In this case, OFDM replaces FDMA with manifold advantages. Currently wideband CDMA (W-CDMA) and OFDM/TDMA techniques are successfully in use in terrestrial mobile multimedia systems. Therefore, these two MASs are getting considerable attention [106] in mobile multimedia communications for nongeostationary satellite interface. In this section we will discuss these multiple-access techniques with their merits and demerits. Based on some recent research work (e.g., [106]), a comparative analysis will also be presented on these two schemes.

1) W-CDMA: W-CDMA follows the same principle of CDMA technique [69], [145]. It gets its name from its wide bandwidth requirement. In CDMA systems, several users simultaneously and asynchronously access a channel by modulating and spreading their information-bearing signals with preassigned spreading code. This spreading code makes the system possible to multiplex several users in the same time and frequency domain. It also aids the system to use multipath diversity reception [1], [145]. In the satellite mobile scenario, each mobile user is assigned with a unique spreading code when it registers with a satellite for communications. While all the registered mobile terminals can transmit simultaneously in the same frequency and time space, the receiver at the satellite can distinguish the individual signals as long as the spreading code assigned to the mobile terminals are mutually orthogonal and the mobile terminals are synchronized.

Multipath fading in the W-CDMA-based system can be substantially reduced because the signal is spread over a large spectrum. On top of that, the system can support multisignaling-rate services simultaneously with frequency reuse feature. In the satellite domain, where multiple signals from different satellites are linearly combined, W-CDMA with universal frequency reuse and a RAKE receiver is very efficient for soft handoff application [53], [146]. In this scenario, in addition to improving the received signal quality, this technique is much better in terms of probability of call dropping than hard handoff from one frequency channel to another, and additionally it simplifies the radio frequency (RF) interface.

Finally, in a W-CDMA-based system, a good synchronization is necessary for the spreading codes to exhibit their mutual orthogonal properties.

2) OFDM/TDMA: The OFDM/TDMA-based system is a combination of OFDM transmission and TDMA techniques, which exploits all the advantages of these two techniques.

Here the overall channel BW is divided into a number of subcarriers, each carrying an individual bit stream with a relatively small signaling rate [26], [103]. In general, within a given time slot, a mobile station may use all or some of the allocated subcarriers; hence, the transmission rate of each mobile station may dynamically vary from slot to slot. This general situation actually represents the OFDM access technique [103].

OFDM/TDMA technology allows transmitting high multiple data rates over extremely hostile channels at a relatively low complexity. Different merits of OFDM system have been discussed in the previous section. On top of those advantages, the combination of TDMA and OFDM techniques provides the advantage of using different time slots and variable transmission rate simultaneously. This extended flexibility and multirate transmission capability of OFDM/TDMA technique calls for very high implementation complexity resulting from the requirement of synchronization between different mobile stations. Besides, we need to consider all the demerits of the OFDM-based system, which are mentioned in the previous section.

3) W-CDMA and OFDM/TDMA: An Analytical Comparison: In the satellite domain, not much research works have been reported on these two MASs, and most of the reported works have presented mainly simulation results [100], [106], [158]. One such work in [106] is worth discussing, where the authors have presented a comparative study between the two aforementioned MASs in a LEO satellite environment. This study has been presented in terms of probability of error (P_b) by considering identical UMTS parameters [1] for both the schemes in the uplink scenario. In this case the simulation results are based on the analysis presented bellow for W-CDMA and OFDM-based systems, respectively.

With BPSK modulated symbols in the W-CDMA environment, the in-phase (I) and quadrature-phase (Q) received signals are given by

$$r_I = S_d\left(I \otimes h_r\right)d - S_c h_i + n_I \tag{3.4}$$

and

$$r_Q = S_d\left(I \otimes h_i\right)d + S_c h_r + n_Q \tag{3.5}$$

respectively, where, d represents the data vector, I represents an identity matrix of size ($N \times N$), N being the data vector length; h_i and h_r are the imaginary and real parts of the discrete-time complex-valued channel impulse response (CIR) vector for the LEO channel; n_I and n_Q are the noise plus interference terms that contain both MAI and AWGN components. S_d and S_c are the Toeplitz matrices defined in terms of the signal spreading code s_d and control spreading code s_c, respectively; while $\otimes$ represents convolution operation. With the applications of (3.4) and (3.5), the estimation $\widehat{h}$, of the LEO satellite CIR vector $h\ (= h_r + jh_i)$ is calculated as

$$\widehat{h} = \left(S_c^T S_c\right)^{-1} S_c^T \left(r_Q - jr_I\right). \tag{3.6}$$

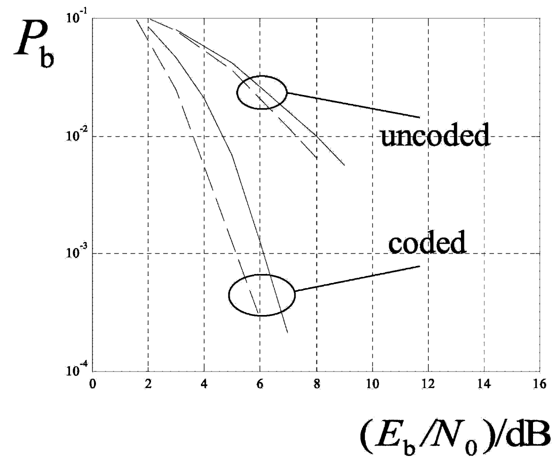


Fig. 10. Uncoded and coded BER performance of W-CDMA with Rayleigh fading (solid lines) and Ricean fading (dashed lines) [106].

Also, channel equalization is performed, by equating the estimate of the data signal vector as

$$\widehat{d} = \left(S_d^T S_d\right)^{-1} S_d^T \left[I \otimes \left(h^H h\right)^{-1} h^H\right] . \left(r_Q + jr_I\right) \tag{3.7}$$

where, the superscripts T and H represent the transpose and Hermitian transpose, respectively.

For the OFDM-based system, upon removing the cyclic prefix, the received signal at subcarrier k, $k = 1, 2, \ldots, K$, in the frequency domain [84] becomes

$$R_k = H_k X_K + N_K \tag{3.8}$$

where X_k and N_k represent the modulated data symbols and the intercell MAI on the kth subcarrier of the received signal, and H_k represents the frequency response of the CIR vector at subcarrier k, which is given by

$$H_k = \sum_{i=1}^{W} h_i \exp\left[-\frac{j2\pi\left(i-1\right)k}{K}\right], k = 1, 2, .., K. \tag{3.9}$$

From (3.9) it is clear that with the appropriate choice of K, the frequency nonselectivity of the LEO channel can be ensured on each subcarrier.

Upon establishing the design parameter of W-CDMA and OFDM systems, it could be shown that the channel estimation and equalization at both the receivers can be applied in a simple and cost-effective way through (3.4), (3.5), and (3.9), respectively. Based on these analytical techniques, the simulation models for both systems have been devised with identical scenarios extracted from the UMTS specifications, allowing a mobile terminal velocity of 20 km/h. In this case, the transmitted bit rate for W-CDMA and OFDM systems are considered to be 120 and 134 kb/s, respectively. At the W-CDMA receiver, a Viterbi decoder has been used to generate the average uncoded and convolutionally coded BER performance curves (Fig. 10) for different signal (bit) to noise energy ratios considering both Rayleigh and Ricean fading channels with a channel bandwidth of 5 MHz. Similar results have been plotted in Fig. 11 for OFDM system. For

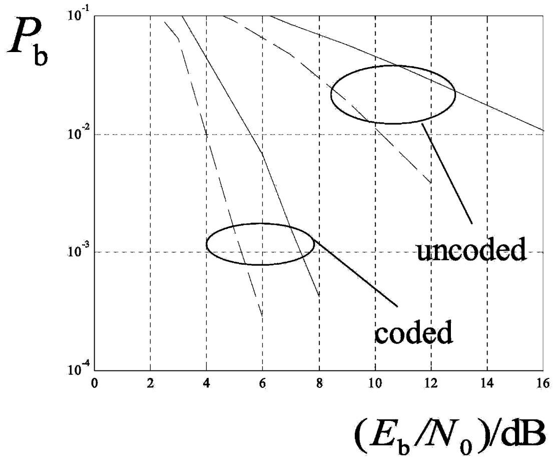


Fig. 11. Uncoded and coded BER performance of OFDM with Rayleigh fading (solid lines) and Ricean fading (dashed lines) [106].

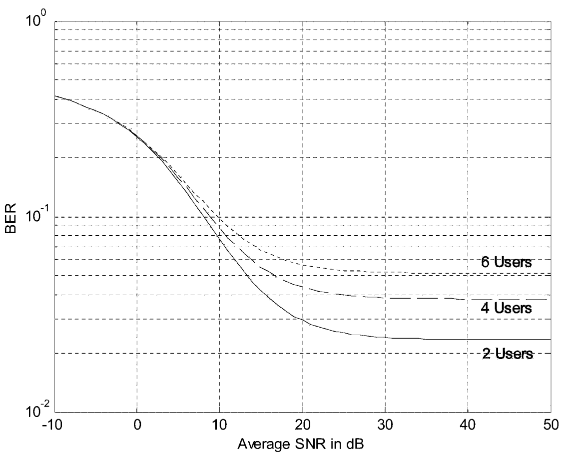


Fig. 12. Effect of the number of users on the BER performance in the QPSK Ricean fading nonlinear satellite channel.

both cases, single-user system has been considered. The simulation results show that with very small performance difference, the BER performance of W-CDMA is slightly better than that of OFDM. These performance differences are observed to be smaller in the Ricean fading channel when channel coding is used.

4) Challenges: From the above analysis it is truly difficult to pick the most appropriate transmission scheme for gigabit-rate applications supporting global mobile multimedia communication via LEO satellite networks. So challenges include further studies on both the uplink and downlink LEO satellite links, by taking into account the capacity, spectrum, and error-rate issues. Besides, many other challenges are to be fulfilled for the MAS issue in the satellite mobile communications area where nonlinearity provides a bottleneck in the power-hungry satellite links. Relating this particular issue for CDMA system, one investigation is already underway in [111] where no interference cancellation or coding technique has been considered. In this work the authors theoretically present the effect of number of users on the BER performance in the nonlinear fading satellite channel (Fig. 12). Another challenging issue would be the designing of spreading coding schemes with very small cross-correlation peak values [43] that would relax the synchronization complexity of the W-CDMA system. A profound research work needs to be carried out to generate this kind of spreading coding schemes. In the case of OFDM/TDMA scheme, besides the implementation complexity, the PAPR and frequency-offset issues of the OFDM technique along with the synchronization issue of the TDMA and OFDM schemes need to be addressed for optimal solutions. A possible approach to reduce the implementation complexity in OFDM/TDMA system would be to use dedicated time-slots for each mobile user [46], [86]. If the shortcomings of the OFDM technique can be overcome, the combination of OFDM and CDMA techniques that results multicarrier CDMA (MC-CDMA) [24], [55], [154], multitone CDMA (MT-CDMA) [112], [142], multicarrier direct-sequence CDMA (MC-DS-CDMA) [39] can be used for both MAS and multiple high bit-rate applications in the satellite mobile domain. Finally, it is important to mention that a major concern on the MAS schemes would be to select the best possible candidate for the 4G scenario, which would need a substantial amount of investigation on this area.

D. Diversity Combining

The major problem, in achieving global coverage for personal communications through nongeostationary satellite constellations, is the path obstruction due to the low elevation angle of the satellites. To overcome this problem, satellite diversity can be introduced. In this case a user can exploit different satellites inside its field of view in order to reduce the probability of paths to the satellites being blocked by natural or artificial obstacles. Moreover, satellite diversity provides very significant gains in the presence of slow fading. For mobile satellite systems, slow fading represents the most power-demanding link condition. With satellite diversity, it is possible to largely counteract these adverse effects with very modest power margins [13]. In this section we will discuss the existing diversity technologies for the satellite mobile communications domain with their merits and demerits. Some challenges for diversity combing will also be addressed in this section.

1) Existing Technologies:

a) Overall Scenario: With the aim to improve overall performance of next-generation communications systems, which is expected to combine satellite and terrestrial domains, the diversity combining technique is extensively considered in the research phase. In this research area, different analytical methods are being proposed and investigated depending on various channel conditions and different LEO and MEO satellite-system constellations (e.g., Iridium and Globalstar[2] [42], ICO,[3] etc). Now that the existing 3G terrestrial systems[4] are mainly based on the CDMA supported architecture, the research focus for the diversity

[2]http://www.boeing.com/defense-space/space/delta/record.htm

[3]http://www.ico.com/overview/index.htm

[4]http://www.3gtoday.com/

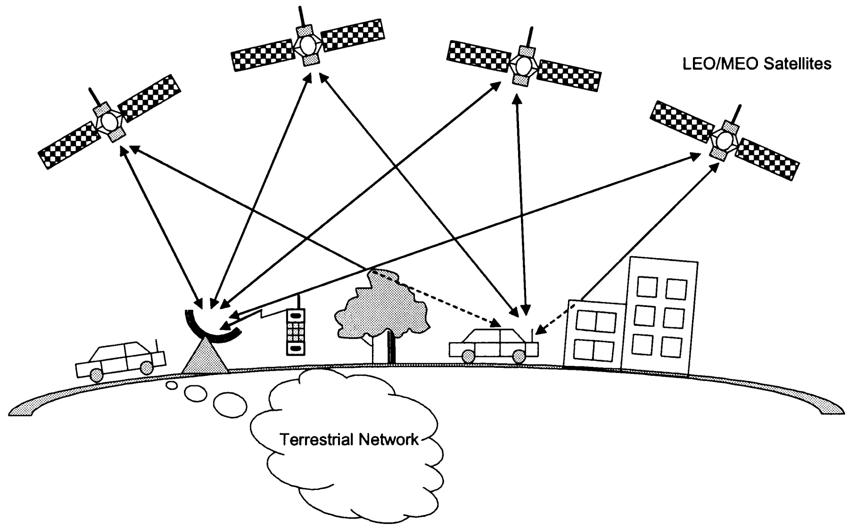


Fig. 13. Satellite diversity system.

combining technique is circling around the spatial diversity technique with the RAKE type receiver in the gateway station. The attention in these investigations is mostly given in the forward link that limits the system's capacity [13] due to the onboard power limitations of the satellite systems. In the case of forward link, the system operator (e.g., gateway station) induces satellite diversity by sending the same signal to different satellites through highly directive antennas.

Fig. 13 illustrates the satellite diversity where the best satellites, i.e., satellites with LOS conditions, are always selected and combined (for only one satellite with LOS, it is simply selection combining) even in a time-varying propagation environment due to mobile terminals. Three popular combining techniques can be carried out at the receiver, which are selection combining (SC), equal gain combining (EGC), and maximal ratio combining (MRC) [11], [113].

b) Spatial Diversity for Satellite Mobile Communications; Technologies in Research: Here, we will mention different spatial diversity combining technologies which are addressed by different researchers, with the aim to integrate the terrestrial 3G mobile communications systems with the satellite domain. In most of these investigations, CDMA technique is considered for all its advantages over other MASs. Globalstar system with diversity combining technique is described in [42] showing that diversity combining is well on its way toward reality. In this paper the authors use space diversity with RAKE receiver both in the mobile terminal and Gateway station. Here the space diversity technique is implemented by combining the convolutionally encoded signals from different satellites with the help of a RAKE receiver.

In [17], the system model for the satellite diversity is based on the consideration that the coverage of the various satellites is only partially overlapping. Here, to evaluate the impact of diversity only the overlapping areas have been considered. The RAKE receiver with MRC is used here. In the analysis it is assumed that the number of fingers in the RAKE receiver is always sufficient to track all the N satellites in view, so that the kth user experiences soft handoff of order N. In this case the ith finger of the RAKE receiver is considered to be tracking the ith satellite. Based on numerical results, it is shown that satellite diversity is not only essential to achieve a satisfactory level of service availability but it is also advantageous to improve the user capacity of the system, particularly in the realistic channel conditions.

The authors in [156] have shown some analytical results on multibranch diversity using MRC combining in a (nonlinear) satellite system considering a fast fading channel environment. The analytical results have been presented in terms of SER where the authors have extended Craig's method [35]. By defining different decision boundaries and subregions for 16QAM constellation, the symbol error probability for the addressed system was shown to be

$$P_e = \sum_{i=1}^{M} \sum_{j=1}^{G_i} \frac{P(s_i)}{2\pi} \cdot \int_0^{\eta_{i,j}} \prod_{l=1}^{L} \int_0^{\infty} f_{\gamma_l}(\gamma_l) \exp\left[-\frac{b_{i,j}\gamma_l \sin^2\psi_{i,j}}{\sin^2(\theta+\psi_{i,j})}\right] d\gamma_l d\theta \quad (3.10)$$

where $P(s_i)$ is the prior probability of transmitted symbol s_i, M represents the array of the MQAM symbols; G_i is the total number of subregions related to symbol s_i [Fig. 14(a)]; γ_l is the instantaneous SNR in lth branch with $l = 1, 2, \ldots, L$, L being the total number of diversity branches; $f_{\gamma_l}(\gamma_l)$ is the pdf of SNR in lth branch, which may correspond to Ricean, Rayleigh, Loos's, or any other fading channel model; $b_{i,j}$, $\eta_{i,j}$, $\psi_{i,j}$ are the constellation and nonlinear function dependent parameters corresponding to symbol s_i and subregion j. Fig. 14(b) and (c) show the SER performance of the system plotted with the aid of (3.10) in terms of diversity in the Ricean fading channel, for two Ricean fading parameters ($K = 8$ dB and $K = 20$ dB), considering linear and nonlinear channel cases. From the figures it can be noted that the diversity combining in the satellite domain improves the performance of the system. This improvement decreases when the Ricean factor increases (this is expected, since the direct

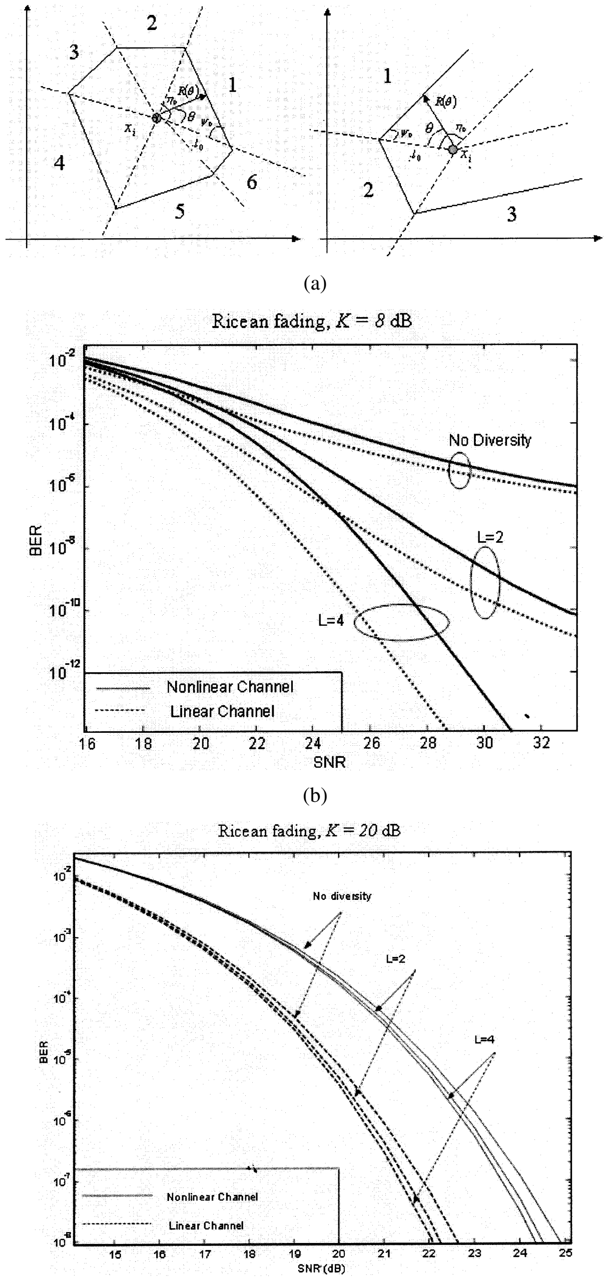


Fig. 14. (a) Illustration of subregions related to symbol x_i: Closed region (left), open region (right). (b) The effect of diversity combining on 16-QAM transmission in the presence of a nonlinear amplifier and Ricean fading, $K = 8$ dB. (c) The effect of diversity combining on 16-QAM transmission in the presence of a nonlinear amplifier and Ricean fading, $K = 20$ dB.

part becomes more dominant, causing higher correlation between paths). It is interesting to note [Fig. 14(b)] that a linear channel with no diversity performs better than the nonlinear channel with two-branch diversity up to a certain SNR (here 20 dB), after which the nonlinear two-branch scheme performs better. The same remark can be drawn for the linear two-branch diversity and the nonlinear four-branch diversity, where the former performs better than the latter up to a certain SNR (here, 24 dB). Therefore, in future satellite mobile systems employing diversity, the amplifier backoff is an additional parameter that should be taken into consideration in the design of the (adaptive) diversity scheme, particularly in situations where the SNR varies through time.

In [83], the effect of diversity combining has been observed by assuming that there are at least two visible satellites at every place on the earth. Here the authors concentrated on the diversity combining upon modeling the satellite channel. At this point, selection type diversity combining is considered. By selecting a satellite with the best operating conditions (specifically if the LOS is available) all the time, it is shown to improve the service availability drastically. To keep the network control complexity to a reasonable level, the authors consider a method, of switching from one satellite to another, based only on changes in the propagation state (i.e., on a long-term fluctuation basis). In this case, due to extremely complex network control overhead, instantaneous switching (may require due to the unavoidable short-term fluctuations in the signal level) or optimal combining by means of diversity is avoided. The authors in [45] have modeled the satellite diversity as a decision-based selection diversity technique where signals from one or more satellites among all N satellites in view are combined upon monitoring the individual SNR values in each branch. In [58], space diversity is used using turbo codes where the coded bits of the two coders are split between different satellites. This coded diversity is compared with the one presented in [42] for Globalstar telephone satellite systems. In [150], an equal gain RAKE receiver is used for the satellite diversity in the uplink.

The authors in [31] and [33] have presented some analytical results considering dual-satellite diversity. In [33] a pilot-aided coherent uplink transmission scheme has been proposed for mobile satellite communications at the L-band. The scheme was designed to enhance link performance as compared to coded noncoherent M-ary orthogonal modulation. An extensive analysis has been carried out for a direct-sequence CDMA convolutionally encoded BPSK link, in a Rice-fading channel with satellite diversity. For the code domain multiplexed pilot (CDMP) aided mode in which a continuous pilot signal with an associated spreading code gets inserted, the bit error probability results have been presented for both slow fading (mobile velocity, $v = 5$ mph) and fast fading ($v = 80$ mph) cases with pilot filter length, $Np = 401$ and the pilot/traffic power ratio $\rho_p = -10$ dB. The results (Figs. 15 and 16) have demonstrated significant diversity gain with only two diversity branches ($L = 2$) for both the settings stated above. In the same figures, along with diversity gains, coding gain has also been confirmed in the presence of convolutional code with rate $\frac{1}{4}$ and constraint length $= 4$, considering different Ricean fading parameters (K).

2) Challenges: Upon adopting the diversity combining in the mobile satellite domain, optimum use of the available satellites to minimize the probability of call dropping, become the main challenging task. In this case, it is necessary to have an efficient handoff algorithm for transferring control from one satellite to another, and more frequently from one beam to another. Although CDMA-based systems are already offering the capability of soft handoffs [53], [146],

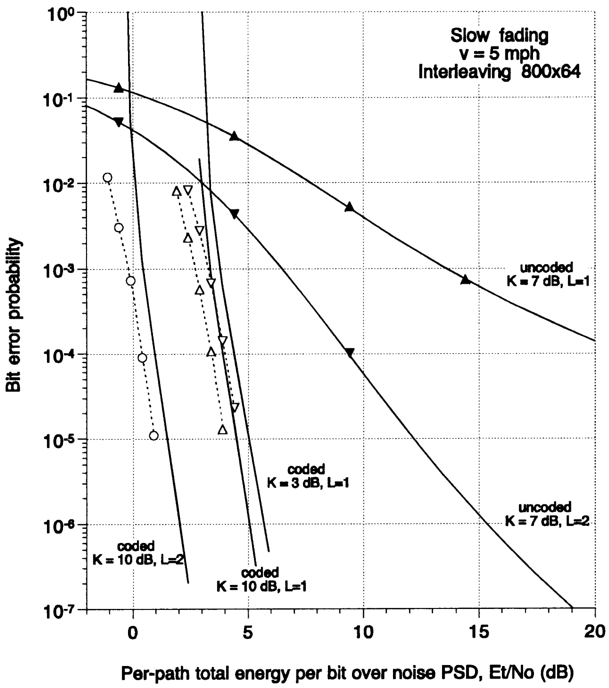


Fig. 15. Error probability performance of the CDMP technique in slow ($v = 5$ mph) Ricean fading channel with $\rho_p = -10$ dB, Np $= 401$; both coded and uncoded performances are reported, with corresponding simulation results [33].

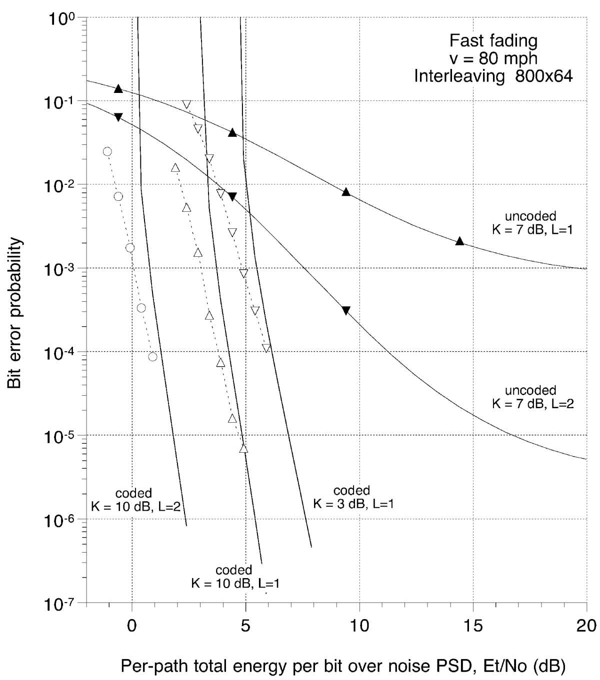


Fig. 16. Error probability performance of the CDMP technique in fast ($v = 80$ mph) Ricean fading channel with $\rho_p = -10$ dB, $N_p = 401$; both coded and uncoded performances are reported, with corresponding simulation results [33].

but when the high bit rate supporting multicarrier modulation techniques are getting the attention [104] for next-generation systems, a substantial amount of research work needs to be carried out to provide satellite diversity considering these modulation techniques. In favorable channel conditions with no critical blockage, satellite diversity may be an unnecessary luxury. It is then up to the system designer to exploit satellite diversity depending on service areas and channel specifications.

E. Performance Criteria

In this section we will discuss the performance criteria issue of a satellite mobile communications system. Performance criteria of a communication system are measured in terms of transmission data rate, BER, capacity, outage probability, range of operation, and resistance to intentional interference (anti-jamming). In this discussion, we will mostly concentrate on the BER performance of the system.

Here, we will first discuss the some simulation results, carried out by Papathanassiou *et al.* [106], for evaluating and comparing the uplink BER performance of W-CDMA and OFDM schemes in the satellite mobile domain. In this case both Rayleigh and Ricean fading LEO uplink channels have been taken into account with coded and uncoded systems. Although W-CDMA achieves more favorable uncoded BER performance than OFDM, this result becomes less pronounced when the coded BER performance is considered. This is due to the increased frequency diversity offered by applying frequency-domain interleaving to the proposed OFDM system. In the case of Ricean fading, the coded BER performance of both systems is comparable. Since the overall BER performance characteristics of both W-CDMA and OFDM are comparable, the final choice between W-CDMA and OFDM for a mobile multimedia communications system based on LEO satellites should be made by performing additional studies with the goal of determining not only the downlink BER performance but also the overall system performance in both links.

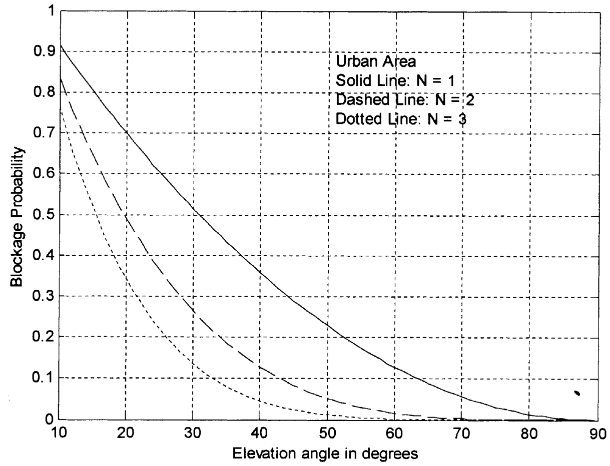
The impact of satellite diversity on both service availability and system capacity has been investigated in [17] by means of analysis and Monte Carlo simulation, considering the effects of path blockage, power control imperfections and fading channel characteristics. In this case, the empirical model for path blockage probability given in [83] is used to show the requirement of satellite diversity both for urban and suburban areas. According to this model, for the kth user and ith path, the path blockage probability is given by

$$P_B(i,k) = \frac{1}{a}\left(90 - \theta_{i,k}\right)^2 \tag{3.11}$$

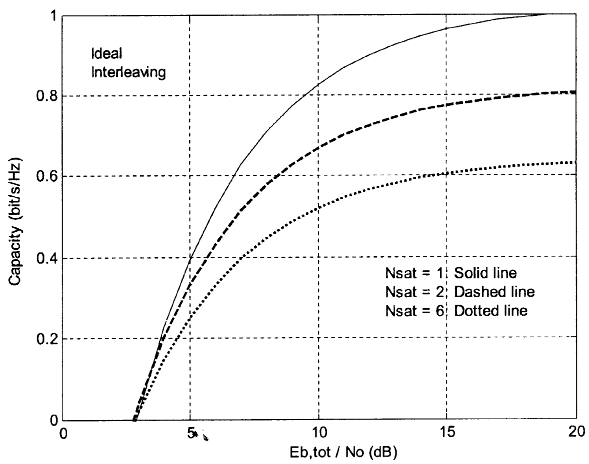
where, $\theta_{i,k} \in [10^0 - 90^0]$ is the elevation angle for the ith satellite in view from the kth user, and a is a normalization factor fitted on measured data ($a = 7000$ in urban areas and $a = 16{,}600$ in suburban areas) [83]. Under the assumption that blockage is independent in different links, the probability for a user to be inactive (completely blocked) can be computed as

$$P_{\text{Block}}(k) = \prod_{i=1}^{N} P_B(i,k) = \frac{1}{a^N}\prod_{i=1}^{N}\left(90 - \theta_{i,k}\right)^2 \tag{3.12}$$

where N is the total number of satellites surrounding the user. Assuming $\theta_{i,k} = \theta$, Fig. 17(a) shows the effect of the



(a)



(b)

Fig. 17. (a) Blockage probability in an urban area, with number of satellites above the minimum elevation angle (10°) as a parameter. (b) The effect of satellite diversity on the capacity with ideal interleaving in the Ricean fading channel with Rice factor of 10 dB, single-link blockage probability of 0.3, normalized interbeam interference of 0.5, and ideal power control.

elevation angle on the blockage probability for a generic user in an urban environment. Considering this path blockage scenario, by only taking into account the active users present in the region of interest, the analysis is carried out on the system capacity. By considering all the resource requirements, the capacity (b/s/Hz) of the CDMA system is obtained theoretically [17] as

$$C=\frac{\exp\left[-h\left(\sigma\sqrt{2}erfc^{-1}(2\gamma)+\frac{h\sigma^2}{2}\right)\right]-\overline{Q(L)}\left(\frac{E_{\mathrm{b,tot}}}{N_0}\right)^{-1}}{\frac{1}{N}\left[\overline{Q(L)L}(1+\varsigma)-\overline{Q(L)}\right]}. \tag{3.13}$$

In (3.13), C can only have values in the range [0, NR_b/W] with N, R_b, and W being the information bit rate, number of satellites in view, and BW of the unspread signal respectively. $Q(L)$ is the required signal-to-noise-plus-interference ratio (SNIR) for the system to achieve a predefined bit error probability P_b in the presence of diversity-order L. $\overline{X}$ represents the statistical average of X. ς is the normalized interbeam interference and σ is the power control error standard deviation. γ is the outage probability and h [$= \ln(10)/10$] is a constant. $E_{\mathrm{b,tot}}/N_0$ is the total average SNR received from all satellites.

By varying different parameters in (3.13), we can see the effects of fading channel characteristics, power control error, interbeam interference, and blockage probability on the capacity of the system. It has been shown that in the Ricean fading channel, assuming ideal interleaving, the satellite diversity decreases the capacity of the system [Fig. 17(b)]. The reason for that is, with ideal interleaving the diversity gain is very small, and as a result, the interference from multiple satellites decreases this capacity. For the fast fading case, the capacity improvement is achieved up to a certain SNR but after that the interference from other satellites takes the control over the diversity gain and, hence, capacity starts to decrease. Similar results have been reported in [45]. In the case of slow fading, large diversity gain is achieved that totally compensates the cochannel interference and, as a result the capacity increases.

The results, on the effect of power control error over the capacity, suggest incorporating efficient power control algorithm. It should be noted that, in the case of the forward link, forwarding the signal through different noncollocated satellites somewhat increases the amount of interbeam interference, thus causing an apparent capacity loss. To counteract this effect of interbeam interference, smart antenna design is suggested by the authors in [17]. In presenting the effect of blockage probability on the capacity, the results show that in practice, for a reasonable probability of single satellite blockage (e.g., 20%) in the Ricean fading channel the overall system capacity multiplied by the probability of having at least one satellite in view (identified as normalized system capacity) is almost independent from the number of satellites providing path diversity. However, with higher satellite blockage probability, the diversity technique increases the normalized system capacity. The results are much more favorable in the slow fading case.

In [63], the BER performance of the satellite system has been studied in terms of availability of a satellite from a user's point of view. The authors have shown that an increase in the mean elevation angles of the nongeostationary satellites substantially increases the BER performance. Simulation results for BER performance analysis is presented in [58] for LEO satellite communications systems with the application of turbo coding for diversity combining. The results show that the processing speed for the turbo-coded scheme is less compared to the Globalstar system counterpart [42]. The former one also performs better in terms of BER.

F. Onboard Processing

Communication satellites have traditionally employed simple bent-pipe transponder relay designs. As mobile global communication systems are becoming more complex, with ever-increasing demands for high data rate transmissions and ubiquitous interactive multimedia services, broadband communication satellites are required in order to better meet the subscribers' needs. The use of sophisticated onboard processing (OBP), onboard switching

(OBS), compatible with existing integrated services digital network (ISDN) infrastructure is, therefore, increasingly becoming necessary.

OBS encompasses several functional areas. These include control of waveguide switching parameters, ephemeris calculations for small beam width, antenna design, communications network protocol management, error detection and correction, flexible buffering and control, digital signal processing, etc.

High-performance OBP technologies enable small and inexpensive mobile terminals to communicate and integrate with various high-speed applications ranging from voice and data to high-speed interactive multimedia. OBP enables the use of spot beam antennas to increase the signal power and directionality. This feature means that ground station size can be decreased, therefore giving rise to lightweight mobile transmitters/receivers that can be carried around. Uplink and downlink are decoupled, which allows them to be optimized separately. With OBP, required transmitter power is reduced, therefore, effects of transponder nonlinearity and adjacent channel interference are reduced [151], [152]. An important feature for future high data rate applications is the flexibility and reconfigurability of OBP devices. This includes, for example, reprogramming of OBP control memories, reconfiguration of earth stations and accommodation of both circuit and packet switched traffic, adopting different flow and congestion control for each zone depending on traffic loads and types, etc. In order to meet future challenges such as high-speed multimedia applications, future OBP should provide services compatible with existing ISDN infrastructure, TCP/IP compatible services for data applications, and point-to-point and point-to-multipoint on-demand video services [152].

Onboard satellite switched networking can be implemented by two methods: fully switched and supported switching. In the fully switched system, the satellite does all the processing and switching, making the satellite more complicated and expensive. This type of OBP exploits satellite technology to its fullest in order to simplify the earth stations. In the supported switching method, some terrestrial controls are used to support the processing onboard the satellite. This allows the processing on the satellite to be much less complicated, and improves its reliability.

OBP can be classified into five main categories [49]: baseband processing and switching, intermediate frequency (IF) or RF switching, fast packet switching, photonic baseband switches, and ATM-oriented switches. IF or RF switching involves electronically controlled RF/IF switches, which can be reconfigured on a near-real-time basis via ground control. In these schemes, both uplinks and downlinks could be TDMA, FDMA, or multifrequency (MF) TDMA.

In the baseband processing and switching, the signal is first demodulated, some error detection and correction are performed using automatic repeat request (ARQ) or other suitable protocols. Then data routing, remodulation, and transmission follow. Since switching takes place at baseband, this allows additional flexibility compared to IF/RF switching. For example, received TDMA signals can be retransmitted through different modulation schemes, symbol rates, and carriers, depending on the downlink propagation channel characteristics, number of users, types of services, etc. Efficient and real-time OBP, therefore, represents a major challenge for future satellite mobile technologies, such as adaptive coded modulation, multicarrier CDMA, and cross-layer design. Depending of the type of traffic, baseband switching can be directed toward circuit or packet oriented traffic. For example, if the satellite traffic is mostly packet-oriented traffic, then a packet switch is more appropriate. For hybrid traffic, hybrid packet/circuit traffic can be a good alternative.

Photonic baseband switches [68], such as TDM-based optical ring switches and wave division multiplexing optical rings, allow high-speed switching for both circuit and packet switches. The capability of optical switches to handle throughput of 100 Gb/s places them as major enabling technologies for gigabit-per-second satellite mobile transmissions.

ATM switches are needed for ATM-based wideband ISDN, where different types of signals are transported in a standard size packet called cell. With the migration toward ATM-based ISDN, efficient ATM switches will be needed to enable gigabit-per-second wireless communications. Therefore, a major challenge in the coming years arises from the fact that users will have heterogeneous traffic (ATM, circuit, or packet based), which complicates OBP [49].

IV. Future Satellite Systems: Architectures, QoS and Resource Management, and Cross-Layer Design

Satellite services in previous-generation systems were limited to low bit-rate applications. In the 4G system, the trend is toward global information networks offering flexible multimedia information services to users on demand, anywhere, anytime. Satellite-based mobile systems will be used in this regard in a complementary mode to the terrestrial system to meet user demands better [95]. Broadband satellite links will also be used as the backbone in the global network, providing ubiquitous multimedia and high-speed data applications [20], [23], [79], [95]. This section gives an overview of satellite systems and the constellations deployed or proposed for deployments, discusses the satellite network aspects, and briefly introduces the QoS requirements.

A. Broadband Satellite Architectures and Constellations

Broadband satellite architectures may be based on ATM with sophisticated OBP, OBS, and intersatellite links (ISLs), while others employ simple bent-pipe transponder relays. The system design choices depend on factors including coverage, cost, user service, and traffic demands. Constellations may be LEO, MEO, geostationary earth orbit (GEO), or combinations thereof, dependent on the required coverage and the supported services.

Future broadband satellite mobile systems will deploy high numbers of satellites in the nongeostationary constellations, such as MEO and LEO. Though the coverage of GEO satellites is a primary advantage over the LEO systems, the

Table 2
Satellite Mobile Communication Systems [56],[76],[80]. (See Also the Web Sites [7],[36],[70],[131])

System	Satellites	Frequency	Modulation and maximal downlink data rates	Access	Network	Capacity
Astrolink	9 GEO	Ka-band	QPSK 10.4 Mb/s	FDMA TDMA	IP/ATM ISDN	6.5 Gb/s
Cyberstar	3 GEO	Ka-band	3 Mb/s	FDMA TDMA	IP/ATM Frame relay	9.6 Gb/s
Spaceway	16 GEO 20 MEO	Ka-band	QPSK 100 Mb/s	FDMA TDMA	IP/ATM ISDN Frame rely	4.4 Gb/s
Skybridge	80 LEO	Ku-band	8-PSK 60 Mb/s	FDMA TDMA CDMA	IP/ATM	4.5 Gb/s
Celestri	63 LEO 1 GEO	Ka-band			IP/ATM ISDN Frame relay	80 Gb/s
Inmarsat	8 GEO	1.5~1.6 GHz	QPSK 64 kb/s	TDMA TDM	ISDN	
Euroskyway	5 GEO	Ka-band	8PSK 32 Mb/s	MF-TDMA TDM	IP/ATM ISDN	45 Gb/s

longer delay of GEO however makes them typically less suitable for mainstream 4G applications such as interactive multimedia than the LEO systems. For satellites in LEO, propagation delay is on the order of 10 ms. In MEO the delay is on the order of 80 ms, and in GEO orbits it is 250–270 ms. Other delays due to processing and transmissions are on the order of 80–100 ms for regional traffics and 140–180 ms for international ones. When all delays are considered GEO satellite-based communications may be marginal for quality due to time delays. However, LEO and MEO orbits have their peculiar problems. Due to the low altitude, LEO and MEO satellites move at rapid speeds, causing frequent handovers between the ground terminal and the satellites, which are in view for a relatively short period. The high mobility causes regular-changing network topology and the transmission is subjected to Doppler shifts and small-scale multipath fading. Additionally, LEO and MEO satellites rely on ISLs between neighboring satellites to increase coverage. The main challenge here lies in the proper handling of ISLs so that they do not lead to problems with delay jitter, which can degrade voice and video QoS performances over the satellite systems. Buffering is a good solution known to work well for jitter problems and must be employed.

Several satellite mobile systems have been deployed, or are in the process of being deployed, employing specific constellations or mixture of constellations carefully selected to achieve as much as possible, combinations of low latency delivery, high capacity, high throughput, and high data rate capabilities. Below are some examples (see Table 2 for more details and examples) [56].

The Spaceway satellite system consists of 16 GEO and 20 MEO operating in the Ka- band and utilizing QPSK modulation. Data rate ranges between 16 kb/s–6 Mb/s uplink and up to 100 Mb/s downlink with a total capacity of 4.4 Gb/s. The system can support high-speed data, Internet, and multimedia applications.

The SkyBridge satellite system has 80 LEO and operates in the Ku- band: 10.7–14.5 GHz, with 8-PSK modulation format. Data transmissions of up to 60 Mb/s in both links for a total capacity of more than 20 million simultaneous users are provided. The system can support interactive multimedia services, Internet, and other high data rate applications.

Future Trends: While earlier satellite systems have been designed and implemented using the C and S band communications, the present system designs focus on the use of K band (Ka and Ku bands) communications. These have resulted in widespread use of very small aperture terminals (VSATs) and have enabled the telecommunications across areas where the terrestrial (cellular) system do not exist and/or are not affordable [95]. The use of even higher frequencies will be increasingly common in the future broadband satellite system, as available spectra becomes scarcer. Higher frequencies will then enable further use of smaller terminals and, potentially, greater mobility.

B. Network Aspects: QoS and Mobility Managements, IP Routing

Two types of network topologies are of interest when discussing data and real-time multimedia services over satellites. Satellite-based subnetworks may be used as the last hop connecting the end users to the Internet or some other networks, or a satellite link may be used as trunk or *backbone* somewhere in the network [85]. These two scenarios are depicted in Fig. 18. In the former case, multimedia or data users access one or more servers through a satellite link, a gateway (GTW), and the Internet or some other terrestrial networks. This scenario is particularly suited to remote areas that would be very expensive to reach with the terrestrial cables or radio links. Communication satellites have particular advantages of large coverage area and information broadcasting capabilities that make all users within the coverage area reachable at the same cost—rendering itself easily to IP services. In the latter case, satellite networks offer carrier services to the Internet services providers. In both cases, cross-data routings between the satellite and the IP network are required. Coordination functions and operations designed to ensure smooth integration of both networks include the use of ISLs to increase coverage and minimize the number of GTW stations; the use of *interworking units* (IWUs) to provide seamless roaming between networks of different standards without interruption in reception of an ongoing service; the use of a *network control station* (NCS) to provide the overall control of satellite network resources and routing operations; the use of onboard satellite processing units to perform multiplexing/demultiplexing, channel coding/decoding, and ATM-like switch by using a multispot beam configuration [78]–[80]. Also included in this series is the use of a *satellite adaptation unit* (SAU) to perform all necessary user terminal protocol adaptation to the satellite system. The SAU can provide an access interface very similar to the standard ATM *user-network interface* (UNI). The SAU also includes several physical layer functions such as channel coding, modulation/demodulation, RF, and antenna processing. The interworking of these systems and functions enables the satellite system to provide mobility and IP routing support as well as reasonable QoS support.

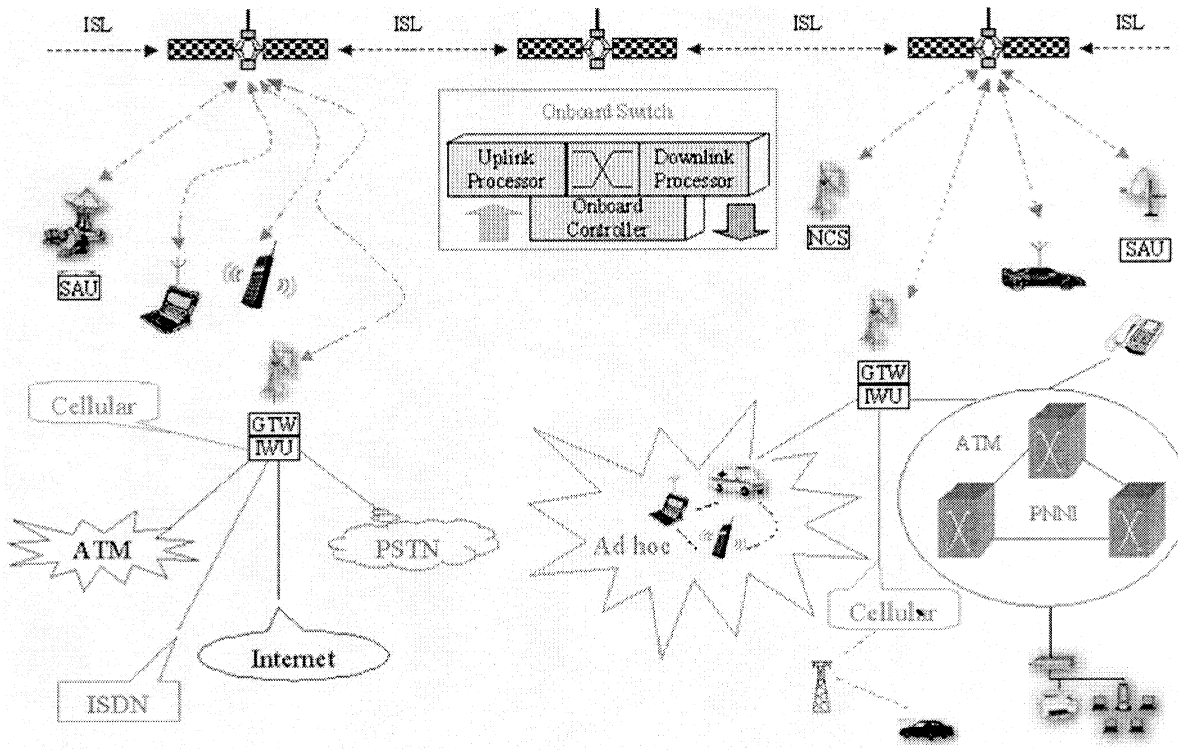


Fig. 18. Interconnection of satellite and different terrestrial networks.

1) Issues Involved in QoS Support: The main issues involved in QoS provisioning is the fact that different traffic types have different QoS requirements, which results in different service levels. Packetized voice traffic is characterized as relatively low bandwidth (typically 8 Kb/s), but requires very low latency delivery to ensure high-quality audio at the destination. Such traffic for example, is tagged high priority to protect its service quality. Video traffic, on the other hand, generally has higher bandwidth (128 to 384 Kb/s or more), but still similarly require low latency for high-quality video images at the destination. Data traffics like file transfer, e-mail messages, etc., can generally be allowed to suffer latency through the network without appreciable QoS deterioration. While an e-mail message is typically low bandwidth, file transfer takes significantly high bandwidth. The goal of resource management for QoS is to share properly and efficiently access to the available resources among these different traffic types with the aim of keeping their required quality. Large packets delivered from a high-bandwidth delay tolerant data service like file transfer, for example, may cause quality-degrading delay to latency intolerant application such as voice. If a 1500-B packet delivered as part of a file transfer over a 64 Kb/s link will take 187 ms to be transmitted, voice and video packets in queue behind this data packet must keep waiting for this time interval. As a result, voice cuts will be heard for the voice traffic, while jitter may be observed in the video images. Effective resource sharing mechanisms, therefore, play important roles in QoS provisioning.

In addition to the foregoing, more recent issues have emerged in QoS provisioning because of the heterogeneous nature of the upcoming 4G system. The 4G system is an integrated network consisting of different constituent networks that are necessarily different in terms of their QoS services. Provisioning of internetwork QoS, through adequate negotiation of QoS parameters and the adherence to the users' and providers' contracts and specifications, as users data traverse the heterogeneous networks remains a major challenge to be addressed.

2) QoS Support in Satellite Systems: Networks primarily offer two types of services: *guaranteed* and *best effort*. In guaranteed service, the network provides some sort of QoS guarantee to individual users or groups of users. These guarantees are often in the form of ensuring that a QoS metric (e.g., the throughput for a group of users or experienced delay is greater/smaller than some given minimum/maximum required threshold [128]. In the best effort service, there is no guarantee on the service level provided by the network. Therefore, the QoS offered to the users is a function of the network status. E-mail services are typically provided on a best effort basis.

4G mobile communication systems will allow real-time processing, high data rate transmissions, and interactive multimedia services, which are less tolerant to delays and symbol errors. These applications, therefore, need some specific network conditions or QoS requirements.

There are two QoS architectures defined for IP networks to meet these challenges: *"intserv"* (integrated services) and *"diffserv"* (differentiated services) [20], [23], [48], [153]. In the *intserv* architecture, the QoS model provides IP applications with strict QoS requirements by requiring applications to set up reservations before transmitting traffics. The most important *intserv* protocol for setting up resource reservation in the network is the *RSVP* (resource reservation protocols).

Intserv QoS model offers a "flat" QoS service for all traffic classes. The *diffserv* architecture, on the other hand, allows IP traffic to be classified into a finite number of priority and/or delay classes. The traffic flows with a higher priority will have a higher probability of passing through the congested routers. Traffic with a given delay priority is scheduled for transmission with higher priority over less delay-sensitive traffic. Depending on the choice of the network operators, some sophisticated versions of this protocol like *expedited forwarding*, *assured forwarding*, or *weighted fair queuing* can be implemented [134].

For data services over WANs (wide area networks) and MANs (metropolitarian area networks), the data traffics from various LANs will have to pass through the network *backbones* which can be frame relay based, satellite based, ATM based, IP based, ISDN based, or any combinations of these. There is, therefore, the need to extend the QoS mechanisms to the satellite networks, ATM networks, etc., so that these backbones will not become bottlenecks for QoS support in the future integrated voice, video, and data services over the IP network. For the ATM network, the need for seamless IP/ATM integration led to the development of the multiprotocol label switching (MPLS) protocol which heralded the convergence of these two networks. This success results today in the wide deployment of ATM backbones in the Internet, and several approaches have been standardized for running IP over ATM networks. For satellite networks, however, some *cross-layer* design issues are still being addressed, the result of which is hoped to be the way forward for future IP over satellite network considerations.

3) Mobility Management: Mobility management consists of two main activities: *location updates (or managements)* and *terminal paging* [87]. In the terrestrial wireless network architecture, the network is divided into some location areas (LAs). One LA may include one or more cells. Location update occurs when a mobile terminal enter a new LA. The newly arrived terminal will update its location in the database. The paging occurs when it is required to locate a user for an incoming call. The network pages all cells to find the exact location of the called terminal. Paging aspect of mobility management is usually coordinated by the routing protocols used. The subject of routing is discussed in the next section.

In the future broadband satellite systems, location (and handoff) managements will be given important consideration because of the potential of heavy overhead consumed in these processes [80], [87], [99]. In the nongeostationary (NGEO) satellite network, location (and handoff) managements are significantly more complex than the terrestrial counterpart. The high speed of the NGEO satellites (e.g., about 2600 km/h for the LEOs), and their relatively short coverage period (e.g., about 10 min for the LEOs) [87] make this task somewhat challenging. Due to the continuous motion of NGEO satellites, their footprints change frequently and the location of the satellites relative to one another changes as well. The satellite network topology or satellite–ISL topology (i.e., number of satellite nodes and ISLs in direct contact with one another), therefore, changes rapidly. This change in satellite–ISL network topology results in an addition of some new ISL connections and rejection of some past ISL connections to the network, thereby requiring handoff and rerouting between two communication endpoints. Consequently, several rerouting and handoff requests are generated during a single communication in a mobile satellite network [80], [87], [99].

Satellite networks with ISL connections present two main types of handoffs: connection handoff and link handoff [99]. For ongoing communications, connection handoff occurs due to the relative motion between an end terminal and its corresponding satellite. The second type of handoff occurs when a satellite approaches the earth pole, and the network needs to release some of its ISLs. Link handoff can be averted to some extent by carefully selecting a particular ISL in the communications path. However, the fact that the satellite follows a fixed trajectory implies that there can be some prediction schemes that perform near optimally in predicting satellite locations and coming up with reasonably accurate representations of the network topology. This is especially true for the NGEO satellite networks. Such information, obtained on a continuous basis, can be used for path selections that avoid unnecessary link handoff. Also, it is quite intuitive to note that maintaining/establishing multiple backup routes at any time instant may be a possible solution to this problem.

4) IP Routing: The inherent time variance of users' traffics on the ISLs presents new challenges for IP routing over satellite network [15], [56], [155]. Topology information, on which terrestrial Internet routing protocols [like open shortest path first (OSPF) and the routing information protocol (RIP)] rely, becomes rapidly obsolete when such protocols are used over satellite networks. Current terrestrial routing protocols are, therefore, not capable of providing QoS guarantees in the satellite domain—especially in the LEO-based satellite networks. In addressing these challenges, various IP routing techniques suited to the satellite systems are currently being studied [56], [155].

In the satellite network, routing may be implemented on the ground or onboard the satellite [onboard routing (OBR)]. In either case, existing information concerning the space segment, e.g., satellite ID and ISL interface, and the ground segment, e.g., geographic position, host ID, and multiple-access information is required [23], [48], [56], [79], [80]). While the IP protocols dominate the end systems attached to the satellite terminals, majority of the proposed satellite systems plan to use ATM as the link layer technology for interconnecting the satellite terminals. This is partly due to the fact that the technologies deployed in these systems, like the use of fast packet switches onboard the satellites, etc., are inherently suited to the ATM systems, and partly due to the fact that at the time of designing these satellite systems, ATM was viewed as the dominant future network technology. The long lead time from the design of satellite systems to development, launching, and service usually make it difficult to implement the latest technology, and in this case has led to the use of an ATM-based transport technology as opposed to IP switching (using MPLS) [155].

Most of the future broadband commercial satellite systems are still expected to be ATM-based. However, switching/IP routing would be accomplished via the use of ingenious protocols designs in conjunction with ATM, IP/ATM, encapsulation, and tunneling. For example, the Teledesic system is expected to employ its own designed protocols for both the ISLs and the space–ground links. Spaceway and Astrolink use ATM-based communication for the ISLs and earth–space links, as well as custom MAC/LLC and custom signaling. SkyBridge employs ATM in the ground segment. Each of these systems is however expected to support IP via tunneling [56].

C. Resource Management

A resource management (RM) entity in a satellite network has two main functions: *resource allocation* and *flow control*. In resource allocation, the entity handles *link access* (assignment) and the associated *scheduling* functions. In this context, various MAC protocols have been used for uplink and downlink assignments in satellite networks. For the uplink access, methods include: *random* (Slotted Aloha) *access*, *dedicated (fixed bandwidth) assignment*, and *dynamic bandwidth assignment* techniques [11], [50], [105]. With the random access method, connections from different terminals broadcast data at the beginning of the next slot following their arrivals. Simultaneous transmission from two or more terminals may occur, and the resulting collisions necessitate retransmissions causing extra delay. Random access methods are not well suited for stringent QoS applications, but have been widely used for *best effort* services due to their simplicity of implementations. With fixed assignment, a terminal's connection is permanently assigned a constant number of slots per frame for the duration of the connection or the life time of the terminal. Examples of this method include FDMA, TDMA, and CDMA techniques. The main advantage of this method is the provision of performance guarantees, but has a major drawback in its low bandwidth efficiency. Methods to bridge gaps between these two performance ends have recently been studied for the terrestrial network [128]. This method, known as multiuser diversity or channel-state-dependent scheduling, uses the concept of "active" and "inactive" channel to select the users to be allocated resources. Users whose channel state information cannot support reliable data transmission (inactive or OFF state) are not allocated bandwidth resources at any time instant. Extension of such methods to the satellite domain will be good considerations for future broadband satellite systems. In the dynamic bandwidth assignment, resource (slot or bandwidth) allocations depend on whether or not there are data packets awaiting service at the connection's (user's) terminal queue. When a user connection has new data arrival, signaling messages are sent to the satellite notifying it of the arrival. Upon receipt of this information, the satellite assigns slots to the connection. The slot assignment here is guaranteed and, therefore, the dynamic assignment method can support QoS traffic. The main difference between the dynamic allocation method and the channel-state-dependent scheduling scheme is the fact that slot assignment in dynamic allocation method is only based upon requests, and information about the user's channel status is not utilized. In dynamic bandwidth assignment, when a connection no longer needs a slot allocated to it during connection establishment, the satellite may assign the slot to other users' connections. The drawback of this scheme is the signaling delay for the call setup (assignment) process, which can typically be 250 ms for GEO satellites. For the downlink access, the fixed bandwidth assignment techniques (*CDMA, TDMA*, *FDMA*, or their hybrids) are typically utilized.

Recently, however, there has been growing interest in hybrid medium access schemes. The distributed coordination function (DCF) and point coordination function (PCF) in IEEE 802.11a/b and the extended DCF (EDCF) and hybrid coordination function (HCF) in IEEE 802.11e are examples of such schemes. The DCF is used during a contention period (CP), whereas the PCF is used during a contention-free period (CFP). The PCF has higher priority over DCF to accommodate time-bounded traffic. The use of interframe spaces/gaps of different lengths allows prioritized medium access. In IEEE 802.11e, the EDCF is used during the CP, but it supports multiple traffic categories of different priorities. Each traffic category has its own virtual transmission queue, and is characterized by a unique arbitration interframe space (AIFS), a minimum contention window (minCW), a maximum contention window (maxCW), and a persistence factor (PF). The access point (AP), or hybrid coordinator (HC), may poll wireless stations during the CFP as the CP. To comply with application QoS requirements, a controlled contention scheme is used. The AP/HC issues a control frame to initiate the controlled contention interval during which nodes can request upcoming contention-free transmission opportunities. In addition, while TDMA, FDMA, and CDMA were originally used as fixed-assignment schemes, hybrids of these techniques have been recently used in a dynamic way. Hybrids of TDMA and CDMA, for example, are deemed very efficient and have been proposed for future all-IP networks. In the same context, UTRA time division duplex (TDD) has been used and in fact standardized by the 3G partnership project (3GPP) for its efficiency and high bandwidth utilization. It facilitates both FCA and DCA of time slots through the use of dynamic switching points in each time frame. This is essential to asymmetric traffic (i.e., uplink and downlink traffic are not similar; e.g., in the case of file uploads and downloads), which is expected to dominate future wireless networks. The tradeoff, of course, is the need for quite sophisticated scheduling techniques. Due to the high propagation delay inherent to satellite communications, however, the above schemes need to be tailored to mobile satellite networks.

Scheduling strategies for broadband satellite communications have not been extensively explored. The main challenge for onboard scheduler designs is the fact that satellite systems are much more limited in link resources and computational capabilities (due to limited power resources) than their terrestrial counterpart. In [98], a simple adaptive bandwidth reservation scheme (ABRS), applicable to both FCA and DCA techniques, is proposed for radio resource management in dynamic satellite networks. In this scheme, when a new call is accepted or released, or a handoff is generated, a metric called mobility reservation status is restructured. This metric provides information about the bandwidth requirements of all active connections in a specific spot beam in addition to the possible bandwidth requirements of mobile terminals currently connected to the neighboring spot beams. ABRS is simple enough to be executed in real time and also provides the flexibility to map, in a dynamic way, the service requirements into the NGEO satellite network performance features. The major advantage of the ABRS lies in the absence of a fixed predefined way of handling calls in a wireless network.

Flow control, on the other hand, deals with the management of the network resources when quality-degrading congestions occur. Congestion problems occur when the demand for resources onboard satellite exceeds its capacity. Congestion can rapidly increase delay and severely degrade QoS. Traffic control functions for managing congestions are in the form of two mechanisms: *proactive* and *reactive*. In the proactive approach, routers in the network indicate congestion by dropping packets (selective cell discard), which in turn causes the source to adaptively decrease its sending rate [128]. Future broadband satellite systems (especially the nongeostationary based) are expected to utilize a reactive form of this control in which explicit congestion notification (ECN) mechanism is included. In the ECN mechanism [128], a TCP packet header has an ECN bit which is set to zero by the source. If the router detects congestion, it will *set the ECN bit to one*, and the packet is said to be marked. The marked packet eventually reaches the destination, which in turn informs the source about the value of the mark (i.e., ECN bit value). The source then adapts its transmission rate depending on the value of the mark. It is noteworthy that flow control is addressed at almost all layers of the OSI protocol stack.

D. Cross-Layer Design Issues

The challenges for future broadband satellite systems is to integrate satellite networks smoothly into the above-mentioned QoS frameworks, while achieving, to the extent possible, efficient use of the precious satellite link resources. Considerable research efforts have been addressing the issue of efficient link resource utilization in satellite network through the use of cross-layer optimization of data transmission (or cross-layer design) [29], [54], [94]. In cross-layer design, the physical and MAC layer knowledge of the wireless medium is shared with higher layers, in order to provide efficient methods of allocating network resources. Thus, optimization of the network layer functionality is performed by means of incorporating unconventional lower layer parameters into the network layer's traditional function.

Joint optimization of data transmissions across various layers right from the application layer down to the physical layer in an IP/satellite integrated network has been considered recently [54], [85]. An observation harnessed for such cross-layer design is the fact that, while the IP or MAC layer does not know the context of a data packet, the application layer does have such information. The application layer knows whether a given packet is the beginning, middle, or end of a long data stream, or whether it is all alone. On the other hand, the physical layer has the knowledge about the amount of link capacity currently available, the BER performance of the wireless link, etc. If joint coordination functions or management interfaces (management I/F) are employed, for example, at the application and physical layers, such that cross-layer exchange of such vital information is achieved, the overall performance of the network will be improved. The idea is as illustrated in Fig. 19. It is important to mention that the management I/F does not only span the application and physical layers. This function can be present in all other OSI protocol entities existing between the application and the physical layers. The main challenge in cross-layer design, however, is how to communicate the auxiliary information through the management I/Fs across the layers, with minimum impact on the standard network protocol stack and using, as far as possible, already existing route reservation protocols like *RSVP*, etc. [85]. Another challenge on cross-layer design consideration is that of interoperability of separate networks implementing various architectures of the design. In addressing this challenge, standardization efforts are already in progress to ensure smooth interoperations of the various architectures [85], [128]. In the following, some examples of cross-layer design schemes proposed in the literature are reviewed.

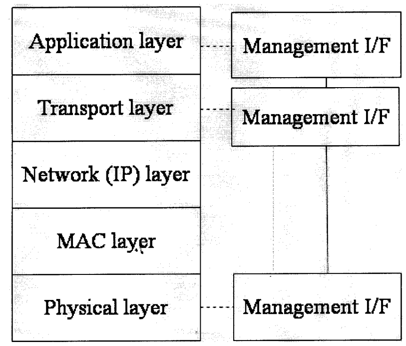


Fig. 19. Cross-layer optimization.

Cross-layer design approaches involving joint network and physical layer optimizations [29], or joint MAC and physical layer optimizations [94] have been proposed. In [29], QoS guarantees for CDMA networks are provided by means of cross-layer optimization across the physical and network layer. At the physical layer, the QoS requirements are specified in terms of a target signal-to-interference ratio (SIR) requirement, and optimal target powers are dynamically adjusted according to the current number of users in the system. At the network layer, both the blocking probabilities as well as call connection delay constraints are considered. In [94], a reservation-based MAC scheme where users reserve data channels through a slotted-ALOHA procedure is introduced. Users request transmissions by sending a signature randomly chosen from a pool of orthogonal codes representing the set of available channels. The

Table 3
State Table for $N = 2, L = 3$

SYMBOL	STATE	Free Channels(f_i)
S_0	[0 0 0]	2
S_1	[0 0 1]	1
S_2	[0 1 0]	1
S_3	[1 0 0]	1
S_4	[0 0 2]	0
S_5	[0 2 0]	0
S_6	[2 0 0]	0
S_7	[0 1 1]	0
S_8	[1 0 1]	0
S_9	[1 1 0]	0

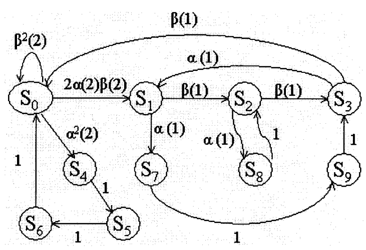


Fig. 20. Markov chain model for traffic statistics-based MAC scheme (for $N = 2, L = 3$ [94]).

base station grants or denies access to users based on (signal strength) measurements at the physical layer and the system information at the MAC layer. Such random access schemes have been proposed for the UMTS-W-CDMA.

One of the difficulties of joint-layer designs in general is the lack of analytical expressions that relate performance parameters across the various layers. An advance in this direction has been recorded in [94] where analytical framework is presented for joint physical and MAC layer designs. The Authors assumed Poisson traffic statistics and observed that if the MAC bases its decisions on the traffic statistics and the received signal power, the transition probability from current state (see Table 3 for illustrations of states) to the next depends only on the two states involved and is independent of the transition history leading to the current state. The MAC scheme can then be modeled as a finite state Markov chain for which a stationary distribution exists. The transition probability from state i to state j is obtained as binomial $(S_j(L), f_i, \alpha_\delta(f_i))$

$$P_{i+1,j+1} = \binom{f_i}{S_j(L)} \alpha_\delta^{S_j(L)}(f_i)\, \beta_\delta^{(f_i - S_j(L))}(f_i) \quad (4.1)$$

where f_i is the number of free channels available while the system is in state i, $\alpha_\delta^{S_j(L)}(f_i)$ is the conditional probability of successfully acknowledging a channel when using a MAC function δ, given that there are $f_i (> 0)$ free channels and the system is in state S_j of slot length L. In the same context, β is similarly used to denote the probability of a channel getting locked. Table 3 illustrates the different states and the free channel available, for the case when the number of codes assigned to the receiver is two ($N = 2$), and state slot length $L = 3$. The corresponding Markov chain diagram for this model is as shown in Fig. 20.

For the case when the number of codes assigned to the receiver is two ($N = 2$), an exact result for the stationary distribution for the system was obtained, which lead to an analytical expression for the MAC throughput as a function of certain MAC parameters. Optimization of the MAC function is then possible, based on the throughput expression, and an optimal randomized MAC function that maps the physical layer measurements and the system states to the probability that a channel is acknowledged can, thus, be obtained by numerical searches using the probabilities from the Markov chain formulation above [29]. The significance of this work is that performance gains from such cross-layer designs can be quantitatively measured as opposed to the heuristic results presented in various similar works.

A number of cross-layer design schemes have also been proposed in the literature, primarily for the wireless ad hoc and multihop networks [118], [120]–[123], [135]. In the following, cross-layer design is explained in the context of optimizing the network layer functionality by means of incorporating unconventional lower layer parameters into layer three's objective function [120]–[123]. First, we note that the data rate (R) is constrained by both the channel bandwidth (W) and the signal-to-interference-and-noise ratio (SINR). The SINR is a function of the thermal noise, background interference, the transmission power of current traffic sources, and the channel gain matrix. Consequently, the decision to maximize the traffic volume reaching the sink per unit time or, equivalently, the good-put, is dependent upon the SINR of all the intermediate links. However, packets are typically transmitted several times before they reach their destinations. Thus, a route that consists of strong links, permitting higher data rates, does not necessarily lead to higher throughput. In addition, the higher the data rate the higher the required SINR and the more the interference experienced by other stations. The hop count must still be considered in the routing decision. While this might be considered near optimal, the contention level experienced by the MAC sublayer must also affect the routing decision. That is to say, a route that is made up of strong physical links and a minimum (or close to minimum) number of hops must also incorporate the per-link contention level experienced at each intermediate node. Power control, by its very nature, affects the connectivity of nodes and thus affects medium access, routing and other higher layer protocols. The integration of power control into routing and MAC is, therefore, essential. In addition, the longevity of the intermediate nodes (which is dependent on their current power capacities and the applications they are presently running), their instantaneous and gross share of the aggregate network traffic loads, and their mobility levels, must all be taken into consideration [123].

Due to the heterogeneity and, thus, complexity of 4G/4G+ wireless networks it is expected that application-layer adaptation to network and access conditions is crucial. QoS support becomes an increasingly challenging issue in the presence of external networks (as explained in Section IV-B). A time-dependent QoS support is an example of the dependency of QoS on variable lower layer performance.

Lower layer adaptation based on higher layer information is also an important research direction to be explored. For example, physical channel sensing mechanisms need to be combined with efficient random access strategies, to ensure that channel utilization is maximized or, at least, enhanced. Here, a measure of the intralayer network design can be defined as the ability of two protocol entities belonging to different wireless stations to exchange information of relevance to their internal operation. This would be significantly useful for medium access control and regulation in which such information may affect the queuing behavior of the MAC entity.

With some modifications, it is expected that some of these schemes may be adapted for use in IP/satellite networks. Cross-layer design will be a general trend in future wireless cellular communications. It is expected, therefore, that future IP/satellite network will involve some forms of cross-layer design implementations, which can improve quite significantly, the performance of the IP-satellite integrated networks.

V. Conclusion

The paper has given an overview of the technologies and challenges of high-speed satellite mobile communications. Different technological advances in the field of satellite mobile communications have been presented in the light of future 4G system requirements. The technologies include modulation and coding schemes, multiple-access techniques, diversity combining, receiver design, and onboard processing. Networking, resource and mobility management, QoS provisioning, and cross-layer designs have been addressed as key factors in future satellite mobile systems. The paper has also discussed some of the challenges, which need good attention in near future for the approaching seamless and ubiquitous global communications systems.

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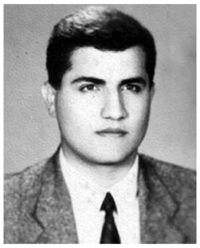

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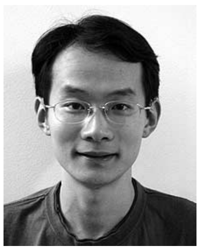

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