Perspectives for Present and Future CDMA-Based Communications Systems

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ABSTRACT

In this article the main boosters of future CDMA communication systems are presented and described in order to highlight ways to cope with the more challenging requirements future systems and services claim. Particular attention is devoted to the inherent weak points of CDMA systems and detection techniques that can be used to overcome their impairments. Moreover, high-data-rate transmissions in wireless channels require proper link adaptation techniques; these are thoroughly described as well. Finally, the last part of this article focuses on the design of suitable protocol strategies for new heterogeneous multimedia packet services characterized by strict QoS requirements.

INTRODUCTION

In recent years the increased demand for advanced wireless communication services has led to the definition of more and more powerful systems. Third-generation (3G) mobile services have just begun, and in the 3G Partnership Project (3GPP) 3G enhancement activity has already started. Furthermore, various wireless research organizations such as the Wireless World Research Forum (WWRF) and International Telecommunication Union (ITU) are holding active discussions about systems beyond 3G to be deployed around 2010. For next-generation mobile wireless systems, high data rates and customizable systems enabled by flexible technologies are envisaged. In order to satisfy the high data rate requirement and efficiently support multimedia services, modulation and multiple access schemes must be spectrally efficient and flexible. Code-division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM) are two of the most promising candidates, as well as hybrid schemes based on both techniques. In particular, CDMA has emerged as the predominant radio access technology to provide multimedia services in 3G systems. However, high-data-rate transmissions with quality of service (QoS) requirements are strongly influenced by the propagation conditions of the mobile wireless channel and multiple access interference due to simultaneous users. As a consequence, to achieve efficient utilization of the limited radio spectrum and allow contemporary connections with different QoS requirements, remarkable improvements in both the wireless physical (advanced detection schemes, multiple antennas, coding, etc.) and link layer (access control, bandwidth allocation, etc.) are required.

This article deals with some of these promising approaches and schemes of special interest in future beyond 3G wireless networks where bursty high-speed traffic is foreseen, and advanced detection schemes and high bandwidth efficiency are pursued. The outline of this article is as follows. We deal with physical layer issuesby providing a brief survey of the principal detection schemes. We also include discussions of the advantages afforded by efficient detection schemes with antenna array systems. We deal with link layer issues: following a brief introduction to the principles of adaptive modulation and coding (AMC), a suitable scheme for efficient AMC implementation in 3G and B3G systems is described. In addition, to increase service reliability, a novel scheme that combines turbo codes' advantages with those of efficient automatic repeat request (ARQ) schemes is discussed. We then deal with radio resource management aspects including admission control, power control, and scheduling schemes. Finally, conclusions are drawn.

PHYSICAL LAYER ISSUES

This section deals with physical layer issues. In particular, some advanced receiving approaches are discussed herein. In addition, a brief discussion of multicarrier CDMA (MC-CDMA) is provided.

ADVANCED DETECTION TECHNIQUES

As is well known, the benefits of the direct sequence (DS)-CDMA technique can be summarized as a potential increase of system capaci-

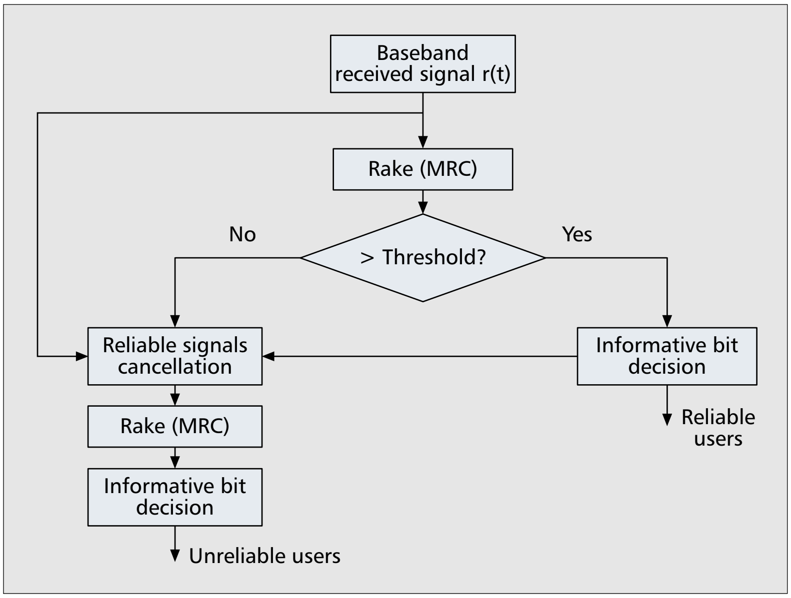

Figure 1. *A block scheme of the SPIC receiver.*

ty, the ability to support universal frequency reuse, graceful degradation under loaded conditions, soft handoff capability, easy adaptation to variable-rate services, low power flux density emission, and finally, the possibility of using classical diversity techniques to cope with multipath fading effects. On the other hand, this technique is basically interference limited (i.e., performance is limited by multiple access interference, MAI). Hence, suitable detection schemes have to be considered in order to lower this drawback.

The traditional DS-CDMA detection technique is based on the use of a correlation receiver in which signals of additional users are considered pure interference. Hence, if a correlator receiver is used, the MAI limits the number of active users in relation to a specified bit error rate (BER) value. Another shortcoming is its vulnerability to the near-far effect (i.e., impairments due to the strongest signals on weak ones), which mandates tight implementation of the power control scheme to prevent performance from excessive degradations. During recent years more efficient detection schemes, multiuser detection (MUD) receivers, have been proposed and investigated as a potential method to improve CDMA system performance [1]. The main feature of MUD receivers is joint detection of all received signals to eliminate the near-far problem and increase system capacity.

The optimal MUD receiver, formed by a bank of matched filters followed by the Viterbi algorithm (i.e., maximum likelihood sequence estimator, MLSE), has implementation complexity (exponential in the number of users) prohibitive for wide adoption in practical applications. Hence, research efforts have focused on suboptimal MUD approaches, classified into linear and interference cancellation (IC) MUD receivers [1]. In linear MUD receiving schemes, a linear transformation is applied to the matched filter outputs to reduce the MAI effects on each user. The two most popular linear detectors are the decorrelating and minimum mean square error (MMSE) detectors [1]. The former performs the inverse of a cross-correlation matrix with matched filter outputs in order to decouple the data. The latter implements linear transformation that minimizes the mean squared error between the actual data and the soft output of the conventional detector.

Interference cancellation receivers explicitly estimate the overall interference due to multiple access and multipath for each received signal, then subtract it from the received signal before making a data decision [1]. IC receivers have lower implementation complexity than linear detectors, so they are widely considered for future applications.

As described in the literature, IC can be performed in parallel (i.e., simultaneously) for all users, resulting in a parallel IC (PIC) receiver, or in a serial way, resulting in a successive IC (SIC) receiver [1].

Of special interest for multirate applications are receivers based on the groupwise approach in which user signals are divided into groups (e.g., according to their spreading factor). Symbol detection and interference estimation are performed for signals within the same group. Hence, the associated interference effects are subtracted from signals in other groups. A special case of groupwise IC receiver is the selective PIC (SPIC) receiver proposed and analyzed in [2, 3]. In this case user signals are divided into reliable and unreliable signal groups based on comparisons of the decision variables with a proper threshold value. Reliable signals are directly detected and (after signal reconstruction) canceled from the whole received signal. Unreliable signals are detected after cancellation of the MAI effects due to reliable signals. In Fig. 1 a block scheme of an SPIC receiver is shown.

It is shown in [3] that the SPIC receiver achieve almost the same performance as the PIC receiver with the advantage of lower implementation complexity.

Recently, advanced receiving schemes have been developed by taking into account that practical CDMA communication systems rely on the use of error control coding and interleaving schemes. Optimal joint decoding/detection methods allow excellent performance to be achieved, but unfortunately require prohibitive computational complexity for actual applications. To lower this drawback, suboptimal solutions in which symbol detection and channel decoding are performed and optimized separately have been proposed [1]. In particular, the successful proposal of turbo codes [4] has led to the definition of powerful MUD receivers based on the iterative (turbo) processing technique. In iterative MUD, extrinsic information is determined in each detection and decoding stage, and used as a priori information for the next iteration. This procedure is adopted at each iteration, as in turbo codes; this detection philosophy is defined as turbo MUD, and the advantages of its introduction are remarkable for heavily loaded systems as well. Even if turbo MUD receivers still have the drawback of high implementation complexity, they represent a promising approach to enhance performance in future high-speed multimedia wireless communication systems by allowing significant gains over classical alternatives [1].

The MUD approach is suited to application at the base station receiver but is not viable in a mobile receiver, so different strategies have been proposed. In particular, growing attention has been devoted recently to adaptive detectors [1]. This type of receiver is based on the MMSE principle between the detector output and the transmitted data, and requires for each user the transmission of a training sequence (TS). Since interference in DS-CDMA is cyclostationary, the receiver only needs to know the training sequence for the user of interest; hence, it can be considered a single-user receiver.

In order to avoid TS transmissions, an MMSE receiver based on the minimization of the output energy (OE), here called a blind adaptive multiuser detector (BA-MUD), has been proposed [5]. In this receiver scheme a convergence procedure to the desired user vector subspace is achieved by exploiting low values of cross-correlation between the informative sequence and interfering user signals, and resorting to a simple implementation of the steepest descent rule.

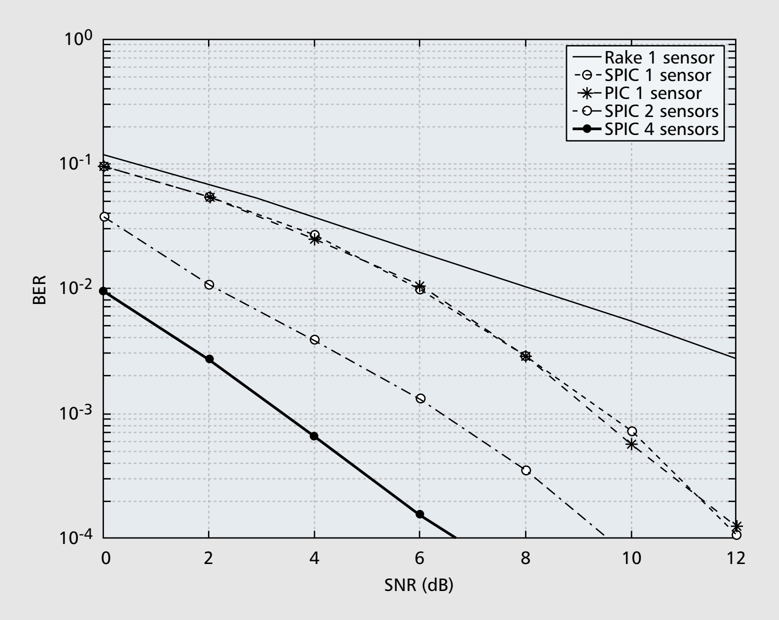

Figure 2. *Performance of the ST-SPIC receiver with multiple antennas in a 10-user system.*

Antenna Systems

The capacity of a wireless system can be increased significantly by smart antennas that mitigate three major impairments caused by the propagation channel: fading, delay spread, and co-channel interference. The use of multiple antenna elements combined with advanced signal processing and coding is usually referred as smart antennas. The basic principle is to multiply the signals at the different antenna branches with complex weights before the signals are transmitted or before the received signals are summed. Antenna array systems can be classified into two categories: diversity and beamforming [6]. Diversity techniques are designed to reduce the fading caused by the wireless channel, increasing the signal-to-noise ratio (SNR) and reducing the probability of deep fades (i.e., signals received from two or more antennas through uncorrelated channels experience independent channel effects). The processing techniques used for diversity are switching diversity and maximum ratio combining. In the former approach the antenna with the best signal is selected; in the latter the signals are weighted before performing signal combining, resulting in the optimum method in the presence of noise. If the signals at the antenna elements have a certain degree of correlation, beamforming techniques are applied. The antenna radiation pattern can be shaped in order to enhance the desired signals and null the effect of interfering signals by means of digital signal processing, combining the signals from different sensors. Therefore, beamforming is effective in multiuser environments when strong interference is present. Beamforming processing can use pilot sequences, adjusting the weights to minimize the MMSE between the known and received signals.

Another approach is multiple-input multiple-output (MIMO) antenna systems in which there are multiple antennas at both the base station and mobile station. MIMO systems promise bandwidth efficiency and improved performance, especially for indoor communications. The key reason for this is that multiple data streams or signals are transmitted over the channel simultaneously. Hence, the capacity of the system is greatly increased. Several techniques for achieving these advantages have been investigated in recent literature, including maximum likelihood detection (MLD) and space time coding [5].

IC schemes could be designed in conjunction with antenna diversity techniques at the base station. The joint use of an antenna array system with an SPIC detection scheme in a typical DS-CDMA communication system is considered in [3] showing the advantage of space combining jointly used with IC. The detector presented in [3], known as space-time SPIC (ST-SPIC), exploits angle of arrival (AOA) information to obtain optimum space combining of all users and the SPIC approach to achieve robust IC among all the combined signals. In the ST-SPIC receiver an optimum beamforming algorithm is implemented before performing IC. This is done to achieve coherent combination of the desired signal replicas by compensating the AOA and an incoherent combination of the interfering signals (i.e., coming from a different direction). The distance between base station and mobiles is assumed to be longer than the antenna separation; thus, fading is assumed to be completely correlated among the different sensors. Figure 2 shows the BER performance of the ST-SPIC receiver endowed with multiple antennas as a function of the SNR at the receiving end. More details can be found in [3].

Multicarrier CDMA

Future generations of wireless systems are expected to support ubiquitous communications, regardless of the propagation environment encountered, while maintaining the required QoS. A promising solution to satisfy these

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requirements is an OFDM-based system. The OFDM technique is robust against severe multipath fading and can be efficiently implemented by means of fast Fourter transform (FFT)/inverse FFT (IFFT). In recent years, multicarrier (MC) systems based on OFDM and CDMA have been the subject of extensive research to efficiently evaluate the feasibility of a such new air interface candidate.

A comprehensive overview of different solutions combining OFDM and CDMA to overcome their inherent limits (e.g., lack of efficient multiple access in OFDM, the near-far effect and cumbersome structure to combat fading in CDMA) was accurately carried out in [7]. Advantages provided by these solutions are efficient exploitation of energy scattered in the frequency domain, robustness toward fading, and the high data rates achievable.

LINK LAYER TOPICS

This section deals with two main link layer topics: adaptive modulation and coding techniques and hybrid ARQ protocols.

ADAPTIVE MODULATION AND CODING TECHNIQUES

Adaptive modulation and coding (AMC) belongs to the class of link adaptation (LA) algorithms. The basic idea behind LA techniques is to adapt transmission parameters to take advantage of channel conditions. The fundamental parameters to be adapted include modulation and coding levels, but other quantities can be adjusted, such as power levels (as in power control), spreading factors, and signaling bandwidth. LA is now widely recognized as a key solution to increase the spectral efficiency of wireless systems. An important indication of the popularity of such techniques is the current proposals for 3G wireless packet data services, such as Universal Mobile Telecommunications System (UMTS), as well as 2.5G, such as General Packet Radio Service (GPRS), to provide a higher data rate.

One of the main challenges for LA is knowledge of the channel parameters, because of delay in feedback response and, on the other hand, channel parameters changing due to the fading nature of the wireless medium.

AMC is one method used in order to perform LA in wireless networks. AMC techniques work by defining some schemes, each characterized by different modulation and coding types (modulation and coding scheme, MCS); in a system where LA is performed using AMC, the best MCS in terms of throughput maximization is selected, considering that in an environment with low SNR it is better to use low-order modulation and coding, while in a high SNR environment it is better to use high-order modulation and coding.

With AMC, the power of the transmitted signal is held constant, but the modulation and coding formats are changed to match the current received signal quality. In a system with AMC, users close to the base station are typically assigned higher-order modulations and high code rates (e.g., 64-quadrature amplitude modulation [QAM] with rate-3/4 convolutional coding), but the modulation order and/or code rate will decrease as distance from the base station increases.

The choice of the best scheme is made according to the measure of some parameters taking into account the channel state information in order to adapt the modulation and coding scheme. The information to be monitored can include a great variety of parameters. For example, a CDMA-based system is more vulnerable to power unbalance, so in its case it is better to monitor the received power fluctuation or multiple access interference.

The channel state information (CSI) can be monitored in two main ways: direct and indirect mode. In direct mode the channel state is measured using some pilot symbols and verifying at the receiving end if the received power is within a specific range, while in the indirect method specific information such as the acknowledgment (ACK)/negative ACK (NACK) packets related to the reliability of the received information are used. Increasing interest in AMC techniques is shown by the attention devoted to them in the definition of some new telecommunications systems such as Enhanced Data Rate for GSM Evolution (EDGE), while for 3G system an extension of UMTS, high-speed downlink packet access (HSDPA), is foreseen based on the use of suitable AMC techniques to improve performance in terms of throughput.

HYBRID ARQ PROTOCOLS

The traditional approach to establish a reliable link-to-link connection is based on adding ARQ protocols to the logical link control (LLC); the basic schemes are Stop and Wait (SW), Go Back *N* (GBN), and Selective Repeat (SR). The above schemes show increasing implementation complexity counterbalanced by better throughput (i.e., lower average number of retransmissions needed to successfully deliver a packet).

The wireless communication paradigm causes bursts of errors to occur during which packets cannot be successfully transmitted on the link, and proper error detection and correction techniques are needed without drastically reducing spectral efficiency.

In this case, to lower residual error rate and hence allow reliable services, powerful channel coding schemes have been proposed [8]; among them, the best candidates seem to be turbo codes [4]. The main drawback of this approach, commonly called forward error correction (FEC), is represented by added redundancy that drastically reduces system throughput. Hybrid ARQ (H-ARQ) techniques keep the advantages offered by previous approaches together with mitigation of the typical drawbacks, thus setting up highly mobile and reliable end-to-end connections.

Basically there are three H-ARQ schemes: type I H-ARQ, in which each packet can be independently decoded, thus discarding erroneous packets; type II H-ARQ, in which joint packet decoding is carried out by keeping track of each message's decoding results in a memory buffer; and type III H-ARQ, in which the MCSs are varied according to the transmission outcome. One of the most promising type II H-ARQ schemes is based on uncorrelated data combination, often called *packet combining*. This permits the Euclidean distance between the codewords and the received sequence to be maximized, as shown in [9], thereby minimizing the erroneous detection probability. Packet combining can be based on either hard decision outputs or on soft channel outputs. In particular, two different type II H-ARQ schemes based on *soft combining* are possible: input and output combined type II ARQ. In the former the additional information to be combined with the actual packet may be a received frame replica, while in the latter it is extrinsic information provided by the decoding of the previous frame. The choice depends mostly on the reliability of the decoding process that can increase or decrease soft output's reliability. As an example, Fig. 3 sketches the block diagram of a receiver scheme in which output combined type II ARQ is adopted.

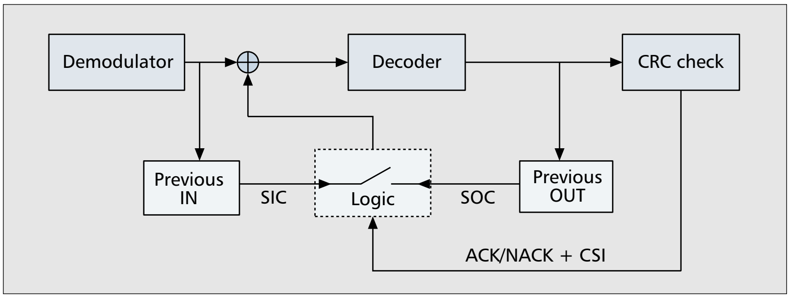

Figure 3. *A receiver scheme with output combined type II ARQ.*

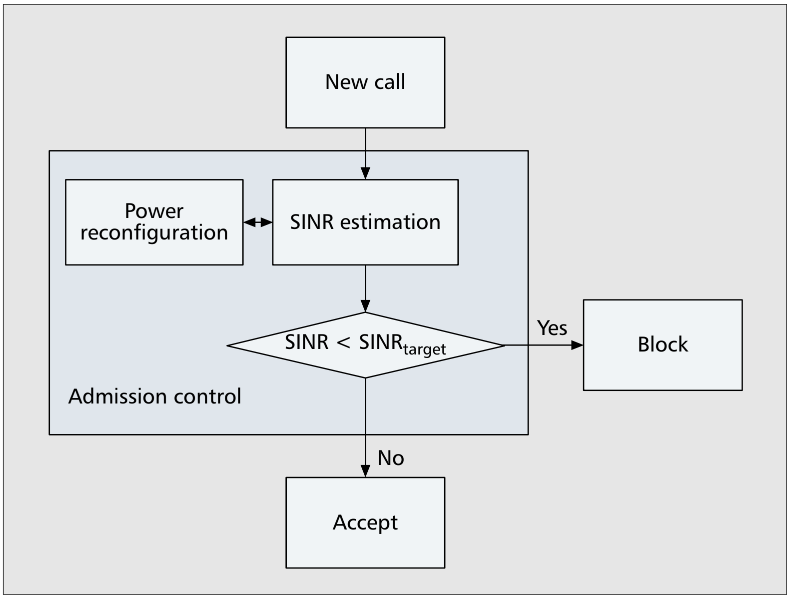

Figure 4. *An admission control scheme.*

Radio Resource Management Aspects

Future wireless systems ought to supply users with a wide range of different multimedia applications, combining real-time with data services and supporting different QoS requirements. As a consequence, flexible radio resource management (RRM) policies, suitable to varying traffic conditions become crucial. RRM functions include all procedures implemented to dynamically manage radio resources in order to meet the instantaneous demands of users moving around in cells, providing data delivery with appropriate end-to-end QoS guarantees. They will impact overall system efficiency, so they will definitely play an important role in future wireless networks [10]. We briefly discuss below three main topics in the definition of a suitable RRM scheme: admission control, power control, and scheduling.

Admission Control

In CDMA systems, where bandwidth is a shared resource, special attention must be paid to MAI arising among active connections. In particular, significant QoS degradations may arise if this parameter is not kept under control by limiting the number of active communications. This goal is achieved by the use of proper admission control (AC) algorithms. The typical AC scheme preserves ongoing connections' QoS by rejecting new connections whenever it is foreseen that they could cause unacceptable degradation of active communications (i.e., outage problems).

The simplest AC allows admission of an incoming request if and only if the total number of users does not exceed a specified limit defined during the network planning phase.

Conversely, dynamic AC algorithms are based on measurements or estimations of the actual system load or interference level, so a variable number of connections may be handled in relation to actual conditions. An alternative approach is that of considering the AC scheme in conjunction with power control or adaptive-rate transmission. As an example of such an approach, Fig. 4 illustrates its basic functional blocks. Typical gain values in terms of additional accepted data connections under very high call traffic load conditions with respect to static approaches are greater than 60 percent.

Power Control

One of the main widely investigated aspects of defined RRM wireless networks is, undoubtedly, power control. In particular, power control is mainly considered in order to improve system performance in a shared scenario. Minimizing power consumption is the main objective of any power control algorithm. This leads to maintaining the necessary QoS by compensating for terminal movements, fluctuating interference, and channel degradation due to shadowing or multipath fading. But the benefits of a proper approach can be various; on one hand, lower power means lower interference and therefore increased network capacity; on the other hand, it reduces the problem of battery life in mobile terminals. Special and more efficient approaches can be applied for multimedia applications whose delay requirements are not too stringent, which is the case for packet communications. Indeed, for this kind of application the QoS parameters are mainly related to the BER, while a certain delay in data transmission can be

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accepted and, in some cases, not even perceived. This peculiarity allows further refinement of PC algorithms suitable for multimedia networks: when observing high interference in the channel, instead of using high power to overcome this noise and transmit a packet successfully, it can be more advisable to postpone transmission, buffer the delay-tolerant traffic, and wait for the interference to subside before transmitting again.

SCHEDULING

Due to the high number of different applications envisaged for next-generation wireless networks, priority-based management of different queues must be supported in order to meet user requirements in terms of QoS and cope with traffic burstiness. Moreover, the management policy of every single buffer must consider the nature of traffic in terms of delay constraints (e.g., real-time or non-real-time applications). Then this approach requires careful monitoring of both channel conditions and buffer occupation in order to efficiently schedule the different types of traffic. A scheduling technique is efficient in any CDMA-based scenario where flexible use of the spectrum could be achieved and different QoS constraints must be satisfied.

CONCLUSIONS

For future next-generation mobile telecommunications, the goals are high data rates and customizable applications enabled by flexible technologies, assuring for the user a ubiquitous system that is able to always guarantee a connection. To realize this aim two possible scenarios are envisioned. One expects the definition of a new standard that substitutes the previous 3G systems and eliminates those problems that make 3G networks unsuitable for high-data-rate multimedia applications. Alternatively, a wireless infrastructure based on the integration and interoperability of different wireless systems can be supposed. Quite apart from which solution will overcome, it seems reasonable that future communications systems will be characterized by highly dynamic resource management and extreme flexibility in deployment and implementation. Hence, CDMA represents one of the most promising technologies for future beyond 3G systems. However, to provide enhanced services with high data rates some key technologies are needed. This article has discussed some of them, such as advanced receivers, multiple antennas, adaptive link layers, and resource management techniques.

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BIOGRAPHIES

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