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SECOND EDITION

3G, HSPA AND FDD VERSUS TDD NETWORKING

smart antennas and adaptive modulation

3G, HSPA and FDD versus TDD Networking

Smart Antennas and Adaptive Modulation

Second Edition

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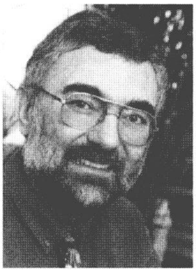
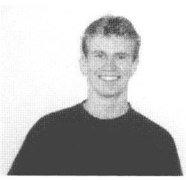
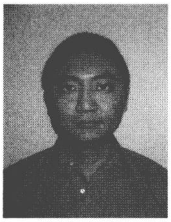
About the Authors



Lajos Hanzo (http://www-mobile.ecs.soton.ac.uk) FREng, FIEEE, FIET, DSc received his degree in electronics in 1976 and his doctorate in 1983. During his 31-year career in telecommunications he has held various research and academic posts in Hungary, Germany and the UK. Since 1986 he has been with the School of Electronics and Computer Science, University of Southampton, UK, where he holds the chair in telecommunications. He has co-authored 15 books on mobile radio communications totalling in excess of 10 000, published in excess of 700 research papers, acted as TPC Chair of IEEE conferences, presented keynote lectures and been awarded a number of distinctions. Currently he is directing an academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council (EPSRC) UK, the European IST Programme and the Mobile Virtual Centre of Excellence (VCE), UK. He is an enthusiastic supporter of industrial and academic liaison and he offers a range of industrial courses. He is also an IEEE Distinguished Lecturer of both the Communications Society (ComSoc) and the Vehicular Technology Society (VTS) as well as a Governor of both ComSoc and the VTS. For further information on research in progress and associated publications please refer to http://www-mobile.ecs.soton.ac.uk



Jonathan Blogh was awarded an MEng. degree with Distinction in Information Engineering from the University of Southampton, UK in 1997. In the same year he was also awarded the IEE Lord Lloyd of Kilgerran Memorial Prize for his interest in and commitment to mobile radio and RF engineering. Between 1997 and 2000 he conducted postgraduate research and in 2001 he earned a PhD in mobile communications at the University of Southampton, UK. His current areas of research include the networking aspects of FDD and TDD mode third generation mobile cellular networks. Following a spell with Radioscape, London, UK, working as a software engineer, currently he is a senior researcher with Anritsu, UK.



Song Ni received his BEng degree in Information detection and instrumentation from Shanghai Jiaotong University in 1999. Subsequently, he was employed by Winbond Electronics (Shanghai) Ltd. as a Software Engineer. His primary responsibility was telecom products R & D. In 2001 he started a PhD on Intelligent Wireless Networking at the University of Southampton, which was sponsored by IST SCOUT project. During four years research, he developed a simulation platform for the UTRA TDD network layer in the UMTS WCDMA system and studied various technologies to enhance achievable performance of UTRA systems. Dr Song Ni is currently a system engineer with Panasonic Mobile Communication, UK.

Other Wiley and IEEE Press Books on Related Topics[1]

- R. Steele, L. Hanzo (Ed): *Mobile Radio Communications: Second and Third Generation Cellular and WATM Systems*, John Wiley and IEEE Press, 2nd edition, 1999, ISBN 07 273-1406-8, 1064 pages.
- L. Hanzo, T.H. Liew, B.L. Yeap: *Turbo Coding, Turbo Equalisation and Space-Time Coding*, John Wiley and IEEE Press, 2002, 751 pages.
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- L. Hanzo, S-X. Ng, T. Keller and W.T. Webb, *Quadrature Amplitude Modulation: From Basics to Adaptive Trellis-Coded, Turbo-Equalised and Space-Time Coded OFDM, CDMA and MC-CDMA Systems*, John Wiley and IEEE Press, 2004, 1105 pages.
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[1]For detailed contents and sample chapters please refer to http://www-mobile.ecs.soton.ac.uk

- L. Hanzo, P.J. Cherriman, J. Streit: *Video Compression and Communications: H.261, H.263, H.264, MPEG4 and HSDPA-Style Adaptive Turbo-Transceivers* John Wiley and IEEE Press, 2nd edition, 2007, 680 pages.

Preface

Background and Overview

Wireless communications is experiencing an explosive growth rate. This high demand for wireless communications services requires increased system capacities. The simplest solution would be to allocate more bandwidth to these services, but the electromagnetic spectrum is a limited resource, which is becoming increasingly congested [1]. Furthermore, the frequency bands to be used for the Third-Generation (3G) wireless services have been auctioned in various European countries, such as Germany and the UK, at an extremely high price. Therefore, the efficient use of the available frequencies is paramount [1, 2].

The digital transmission techniques of the Second-Generation (2G) mobile radio networks have already improved upon the capacity and voice quality attained by the analog mobile radio systems of the first generation. However, more efficient techniques allowing multiple users to share the available frequencies are necessary. Classic techniques of supporting a multiplicity of users are frequency, time, polarization, code or spatial division multiple access [3]. In Frequency Division Multiple (FDMA) Access [4, 5] the available frequency spectrum is divided into frequency bands, each of which is used by a different user. Time Division Multiple Access (TDMA) [4,5] allocates each user a given period of time, referred to as a timeslot, over which their transmission may take place. The transmitter must be able to store the data to be transmitted and then transmit it at a proportionately increased rate during its timeslot constituting a fraction of the TDMA frame duration. Alternatively, Code Division Multiple Access (CDMA) [4, 5] allocates each user a unique code. This code is then used to spread the data over a wide bandwidth shared with all users. For detecting the transmitted data the same unique code, often referred to as the user signature, must be used.

The increasing demand for spectrally efficient mobile communications systems motivates our quest for more powerful techniques. With the aid of spatial processing at a cell site, optimum receive and transmit beams can be used for improving the system's performance in terms of the achievable capacity and the Quality of Service (QoS) measures. This approach is usually referred to as Spatial Division Multiple Access (SDMA) [3, 6], which enables multiple users in the same cell to be accommodated on the same frequency and timeslot by exploiting the spatial selectivity properties offered by adaptive antennas [7]. In contrast, if the desired signal and interferers occupy the same frequency band and timeslot, then "temporal filtering" cannot be used to separate the signal from the interference. However, the desired and interfering signals usually originate from different spatial locations and this spatial separation may be exploited in order to separate the desired signal from the interference using a "spatially selective filter" at the receiver [8–10]. As a result, given a sufficiently large distance between two users communicating in the same frequency band, there will be negligible interference between them. The higher the number of cells in a region, owing to using small cells, the more frequently the same frequency is re-used and, hence, the higher the teletraffic density per unit area that can be carried.

However, the distance between co-channel cells must be sufficiently high so that the intra-cell interference becomes lower than its maximum acceptable limit [3]. Therefore, the number of cells in a geographic area is limited by the base stations' transmission power level. A method of increasing the system's capacity is to use 120° sectorial beams at different carrier frequencies [11]. Each of the sectorial beams may serve the same number of users as supported in ordinary omni-directional cells, while the Signal-to-Interference Ratio (SIR) can be increased owing to the antenna's directionality. The ultimate solution, however, is to use independently steered high-gain beams for tracking the individual users [3] roaming in the network.

High Speed Downlink Packet Access (HSDPA)-style Adaptive Quadrature Amplitude Modulation (AQAM) [12, 13] is another technique that is capable of increasing the achievable spectral efficiency. The philosophy behind adaptive modulation is to select a specific modulation mode, from a set of modes, according to the instantaneous radio channel quality [12, 13]. Thus, if the channel quality exhibits a high instantaneous Signal-to-Interface plus Noise Ratio (SINR), then a high-order modulation mode may be employed, enabling the exploitation of the temporarily high channel capacity. In contrast, if the channel has a low instantaneous SINR, using a high-order modulation mode would result in an unacceptably high Frame Error Ratio (FER) and, hence, a more robust, but lower throughput modulation mode would be invoked. Therefore, adaptive modulation not only combats the effects of a poor quality channel, but also attempts to maximize the throughput, whilst maintaining a given target FER. Thus, there is a trade-off between the mean FER and the data throughput, which is governed by the modem mode switching thresholds. These switching thresholds define the SINRs, at which the instantaneous channel quality requires the current modulation mode to be changed, i.e. where an alternative AQAM mode must be invoked.

A more explicit representation of the wideband HSDPA-style AQAM mode switching regime is shown in Figure 1, which displays the variation of the modulation mode with respect to the near-instantaneous SINR at average channel SNRs of 10 and 20 dB. In this figure, it can be seen explicitly that the lower-order modulation modes were chosen when the pseudo-SNR was low. In contrast, when the pseudo-SNR was high, the higher-order modulation modes were selected in order to increase the transmission throughput. This figure can also be used to exemplify the application of wideband AQAM in an indoor and outdoor environment. In this respect, Figure 1(a) can be used to characterize a hostile low-SINR outdoor environment, where the average channel quality was low. This resulted in the utilization of predominantly more robust modulation modes, such as Binary Phase Shift Keying (BPSK) and 4 Quadrature Amplitude Modulation (4QAM). Conversely, a less hostile high-SINR indoor environment is exemplified by Figure 1(b), where the channel quality was consistently higher. As a result, the wideband AQAM regime can adapt by suitably invoking higher-order modulation modes, as evidenced by Figure 1(b). Again, this simple example demonstrated that

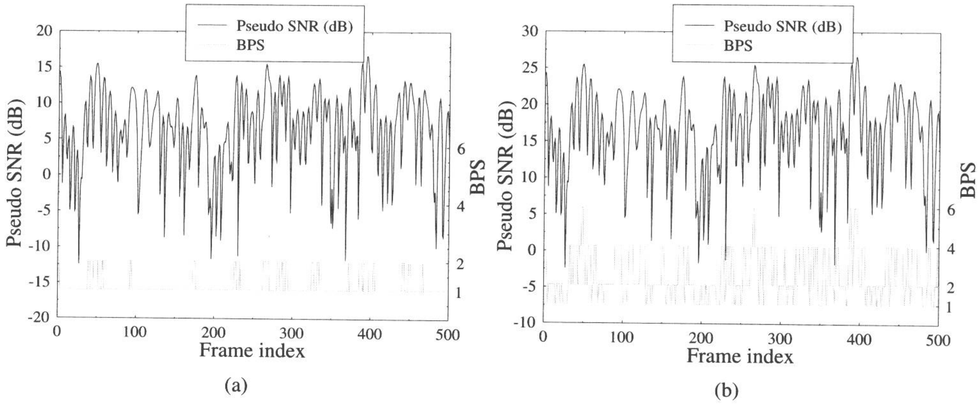

Figure 1: Modulation mode variation with respect to the pseudo-SNR evaluated at the output of the channel equalizer of a wideband AQAM modem for transmission over the TU Rayleigh fading channel. The Bits per symbol (BPS) throughputs of 1, 2, 4 and 6 represent BPSK, 4QAM, 16QAM and 64QAM, respectively. Channel SNR of (a) 10 dB and (b) 20 dB.

HSDPA-style wideband AQAM can be utilized in order to provide a seamless, near-instantaneous reconfiguration for example between indoor and outdoor environments. The most convincing argument in favor of HSDPA-style AQAM is that a fixed-mode system would increase the required uplink (UL) or downlink (DL) transmit power for the sake of maintaining a given user's target Bit Error Ratio (BER), hence the system is expected to inflict a higher Multi-User Interface (MUI) upon all other system users. Therefore, all of the other users would in turn also increase their power requirement, which may result in a system instability. In contrast, an AQAM system would simply adjust the AQAM mode used, in order to use the system's resources as judiciously as possible.

In this book we study the network capacity gains that may be achieved with the advent of adaptive antenna arrays and HSDPA-style adaptive modulation techniques in both FDMA/TDMA and CDMA-based mobile cellular networks employing Frequency Division Duplexing (FDD) as well as Time Division Duplexing (TDD). The advantages of employing adaptive antennas are multifold, as outlined in the following.

Reduction of Co-channel Interference

Antenna arrays employed by the base station allow the implementation of spatial filtering, as shown in Figure 2, which may be exploited in both transmitting as well as receiving modes in order to reduce co-channel interferences [1, 2, 14, 15] experienced in the UL and DL of wireless systems. When transmitting with an increased antenna gain in a certain direction of the DL, the base station's antenna is used to focus the radiated energy in order to form a high-gain directive beam in the area where the mobile receiver is likely to be. This, in turn, implies that there is a reduced amount of radiated energy and, hence, reduced interference inflicted upon the mobile receivers roaming in other directions where the directive beam has a lower gain. The co-channel interference generated by the base station in its transmit

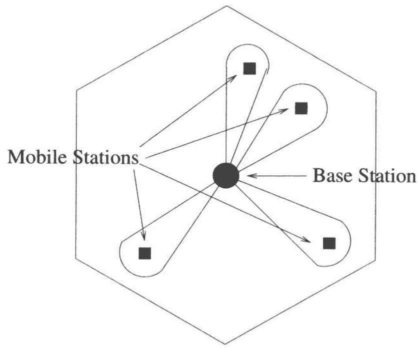

Figure 2: A cell layout showing how an antenna array can support many users on the same carrier frequency and timeslot with the advent of spatial filtering or SDMA.

mode may be further reduced by forming beams exhibiting nulls in the directions of other receivers [6, 16]. This scheme deliberately reduces the transmitted energy in the direction of co-channel receivers and, hence, requires prior knowledge of their positions.

The employment of antenna arrays at the base station for reducing the co-channel interference in its receive mode has been also reported widely [1, 2, 6, 16–18]. This technique does not require explicit knowledge of the co-channel interference signal itself, however, it has to possess information concerning the desired signal, such as the direction of its source, a reference signal, such as a channel sounding sequence, or a signal that is highly correlated with the desired signal.

Capacity Improvement and Spectral Efficiency

The spectral efficiency of a wireless network refers to the amount of traffic a given system having a certain spectral allocation could handle. An increase in the number of users of the mobile communications system without a loss of performance increases the spectral efficiency. Channel capacity refers to the maximum data rate a channel of a given bandwidth can sustain. An improved channel capacity leads to an ability to support more users of a specified data rate, implying a better spectral efficiency. The increased QoS that results from the reduced co-channel interference and reduced multipath fading [18, 19] upon using smart antennas may be exchanged for an increased number of users [2, 20].

Increase of Transmission Efficiency

An antenna array is directive in its nature, having a high gain in the direction where the beam is pointing. This property may be exploited in order to extend the range of the base station, resulting in a larger cell size or may be used to reduce the transmitted power of the mobiles. The employment of a directive antenna allows the base station to receive weaker signals than an omni-directional antenna. This implies that the mobile can transmit at a lower power and its battery recharge period becomes longer, or it would be able to use a smaller battery, resulting in a smaller size and weight, which is important for hand-held mobiles.

A corresponding reduction in the power transmitted from the base station allows the use of electronic components having lower power ratings and, therefore, lower cost.

Reduction of the Number of Handovers

When the amount of traffic in a cell exceeds the cell's capacity, cell splitting is often used in order to create new cells [2], each with its own base station and frequency assignment. The reduction in cell size leads to an increase in the number of handovers performed. By using antenna arrays for increasing the user capacity of a cell [1] the number of handovers required may actually be reduced. More explicitly, since each antenna beam tracks a mobile [2], no handover is necessary, unless different beams using the same frequency cross each other.

Avoiding Transmission Errors

When the instantaneous channel quality is low, conventional fixed-mode transceivers typically inflict a burst of transmission errors. In contrast, adaptive transceivers avoid this problem by reducing the number of transmitted bits per symbol, or even by disabling transmissions temporarily. The associated throughput loss can be compensated for by transmitting a higher number of bits per symbol during the periods of relatively high channel qualities. This advantageous property manifests itself also in terms of an improved service quality, which is quantified in this book in terms of the achievable video quality.

However, realistic propagation scenarios are significantly more complex than that depicted in Figure 2. Specifically, both the desired signal and the interference sources experience multipath propagation, resulting in a high number of received uplink signals impinging upon the base station's receiver antenna array. A result of the increased number of received uplink signals is that the limited degrees of freedom of the base station's adaptive antenna array are exhausted, resulting in reduced nulling of the interference sources. A solution to this limitation is to increase the number of antenna elements in the base station's adaptive array, although this has the side effect of raising the cost and complexity of the array. In a macro-cellular system it may be possible to neglect multipath rays arriving at the base station from interfering sources, since the majority of the scatterers are located close to the mobile station [21]. In contrast, in a micro-cellular system the scatterers are located in both the region of the reduced-elevation base station and that of the mobile, and hence multipath propagation must be considered. Figure 3 shows a realistic propagation environment for both the UL and the DL, with the multipath components of the desired signal and interference signals clearly illustrated, where the UL and DL multipath components were assumed to be identical for the sake of simplicity. Naturally, this is not always the case and, hence, we investigate the potential performance gains, when the UL and DL beamforms are determined independently.

To elaborate a little further, the design of wireless networks is based on a complex interplay of the various performance metrics as well as on a range of other often contradictory trade-offs, which are summarized in the stylized illustration seen in Figure 7.4. For example, Figure 7.4 suggests that it is always possible to reduce the call dropping probability by increasing the call blocking probability, since this implies admitting less users to the system. In contrast, we may admit more users to the system for the sake of reducing the call blocking probability, which however results in an increased call dropping probability. Furthermore,

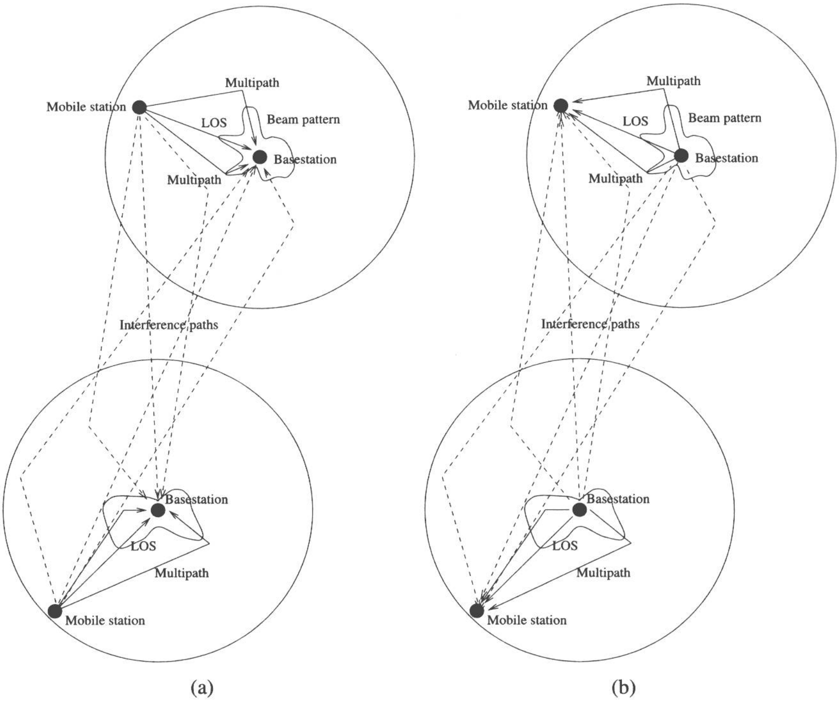

Figure 3: The multipath environments of both (a) the UL and (b) the DL, showing the multipath components of the desired signals, the line-of-sight interference and the associated base station antenna array beam patterns.

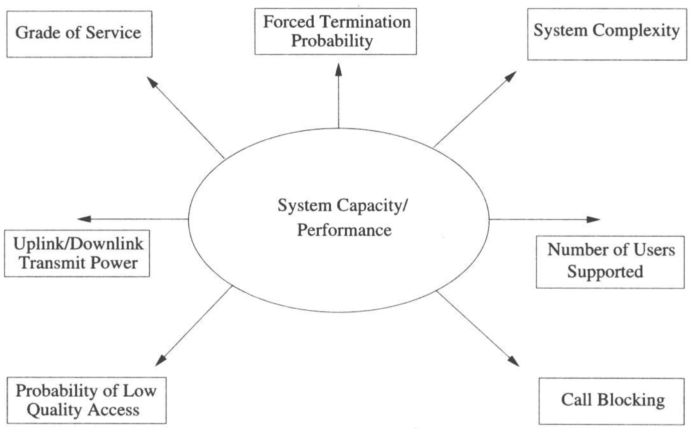

Figure 4: System capacity/performance illustration factors.

the performance of the entire system may also be improved by increasing the system's complexity upon using more intelligent, but more complex signal processing algorithms, such as the beamforming and HSDPA-style adaptive modulation aided transceiver techniques advocated throughout the book, more specifically for example in Chapters 6 and 8. Similarly, the Genetic Algorithm (GA)-based intelligent scheduling techniques of Chapter 10 may be used for reducing the co-channel interference experienced by the system and, hence, for increasing the number of users, and/or for improving the call blocking and call dropping performance. Still continuing our discourse in the spirit of Figure 4, the number of users supported may also be increased, provided that an increased probability of low-quality access value may be tolerated. A whole raft of further similar comments may be made in the context of Figure 4, which will emanate from our detailed discourse throughout the forthcoming chapters. Hence, we postpone the discussion of these detailed findings to our forthcoming chapters.

The various contributions on the network performance of the UMTS Terrestrial Radio Access (UTRA) FDD and TDD modes are summarized in Table 1.

The Outline of the Book

- **Chapter 1.** Following a brief introduction to the principles of CDMA the three most important 3G wireless standards, namely UTRA, IMT 2000 and cdma 2000 are characterized. The range of various transport and physical channels, the multiplexing of various services for transmission, the aspects of channel coding are discussed. The various options available for supporting variable rates and a range QoS are highlighted. The UL and DL modulation and spreading schemes are described and UTRA and IMT 2000 are compared in terms of the various solutions standardized. The chapter closes with a similar portrayal of the pan-American cdma 2000 system.

- **Chapter 2.** Since the standardization of the 3G systems substantial technological advances have been made in adaptive modulation and coding techniques, which may be employed to compensate for the inevitably time-variant channel quality fluctuations of wireless channels. These advances led to the definition of the HSDPA and HSUPA modes, which are detailed in this chapter. The HSDPA mode is capable of supporting a bitrates up to about 14 MBit/s with the aid of adaptive modulation. In contrast, the UL dispenses with the employment of adaptive modulation in the interest of avoiding the application of low-efficiency, power-hungry class-A amplification in the mobile terminal. It rather employs multiple spreading sequences to increase the achievable UL bitrate, which may reach about 4 MBit/s.

- **Chapter 3.** Following the portrayal of the HSDPA/High Speed Uplink Packet Access (HSUPA) standards, in this chapter the HSDPA-style adaptive modulation techniques are further detailed, which are invoked in an effort to compensate for the inevitably time-variant channel quality fluctuations of wireless channels. In this chapter we have not restricted ourselves to standardized solutions, we have rather provided an evolutionary landscape, speculating on the types of more advanced solutions that might find their way into future standards, such as the extensions of the 3GPP Long-Term Evolution (LTE) project or the IEEE 802.11 Wireless Local Area Network (WLAN) standards. We commence our discourse by briefly reviewing the state-of-the-art in

Table 1: Contributions on the network performance of UTRA FDD and TDD cellular systems.

Year	Author	Contribution
1998	Ojanpera and Prasad [22]	An overview of 3G wireless personal communications systems was presented.
	Dahlman, Gudmundson, Nilsson and Skold [23]	Wideband Code Division Multiple Access (WCDMA) was presented as a mature technology to provide the basis for the Universal Mobile Telecommunications System (UMTS)/IMT-2000 standards.
	Brand and Aghvami [24]	Multidimensional Packet Reservation Multiple Access (PRMA) was proposed as a Medium Access Control (MAC) strategy for the UL channel of the UTRA TDD/CDMA mode.
	Markoulidakis, Menolascino, Galliano and Pizarroso [25]	An efficient network planning methodology applied to the UTRA specifications was proposed.
1999	Mestre, Najar, Anton and Fonollosa [26]	A semi-blind beamforming technique was proposed for the UTRA FDD system.
	Akhtar and Zeghlache [27]	A network capacity study of the UTRA WCDMA system was presented.
	Berens, Bing, Michel,Worm and Baier [28]	The performance of low-complexity turbo-codes employed in the UTRA TDD mode was studied.
2000	Haardt and Mohr [29]	An overview of UMTS as specified by the Third Generation Partnership Project (3GPP) was presented.
	Holma, Heikkinen, Lehtinen and Toskala [30]	An interference study of the UTRA TDD system based on simulations was provided.
	Aguado, O'Farrell and Harris [31]	An investigation into the impact of mixed traffic on the UTRA system's performance was presented.
2001	Haas and McLaughlin [32]	The "TS-opposing" DCA algorithm was proposed for a TD-CDMA/TDD air–interface.
	Guenach and Vandendorpe [33]	The DL performance of the conventional Rake receiver was investigated in the context of the UTRA-WCDMA system.
	Poza, Heras, Lablanca and Lopez [34]	An analytical DL interference estimation technique was proposed for the UMTS system.
2002	Perez-Romero, Sallent, Agusti and Sanchez [35]	Congestion control mechanisms were proposed and analyzed designed for the UTRA FDD system.
	Allen, Beach and Karlsson [36]	The outage imposed by beamformer-based smart antennas was studied in a UTRA FDD macro-cell environment.
	Ruiz-Garcia, Romero-Jerez and Diaz-Estrella [37]	The effect of the MAC on QoS guarantees was investigated in order to handle multimedia traffic in the UTRA system.

Table 1: Continued

Year	Author	Contribution
2002	Ebner, Rohling, Halfmann and Lott [38]	Solutions for the synchronization of *ad hoc* networks based on the UTRA TDD system were proposed.
2003	Agnetis, Brogi, Ciaschetti Detti and Giambene [39]	A frame-by-frame exact DL scheduling algorithm considering different traffic QoS levels was proposed.
	Kao and Mar [40]	An intelligent MAC protocol based on cascade fuzzy-logic-control (CFLC) and designed for the UTRA TDD mode was presented.
	Blogh and Hanzo [41]	The adaptive antenna array and adaptive modulation-aided network performance of a UTRA FDD system was investigated.
	Rummler, Chung and Aghvami [42]	A new multicast protocol contrived for UMTS was proposed.
2004	Yang and Yum [43]	A flexible OVSF spreading code assignment designed for multirate traffic in the UTRA system was proposed.
	Sivarajah and Al-Raweshidy [44]	A comparative analysis of different Dynamic Channel Assignment (DCA) schemes conceived for supporting ongoing calls in a UTRA TDD system was presented.
	Yang and Yum [45]	A power-ramping scheme contrived for the UTRA FDD random access channel was proposed.
2005	Ni and Hanzo [46]	A genetic algorithm-aided timeslot scheduling scheme designed for UTRA TDD CDMA networks was proposed.
	Rouse, S. McLaughlin and Band [47]	A network topology was investigated that allows both peer-to-peer and non-local traffic in a TDD CDMA system.
	Zhang, Tao, Wang and Li [48]	Developments beyond 3G mobile proposed by the Chinese communications TDD Special Work Group were disseminated.

near-instantaneously adaptive modulation and introduce the associated principles. We then apply the AQAM philosophy in the context of CDMA as well as Orthogonal Frequency Division Multiplexing (OFDM) and quantify the service-related benefits of adaptive transceivers in terms of the achievable video quality. The associated application examples demonstrate the potential of the proposed adaptive techniques in terms of tangible service quality improvements.

- **Chapter 4.** The principles behind beamforming and the various techniques by which it may be implemented are presented. From this the concept of adaptive beamforming is developed, and temporal as well as spatial reference techniques are examined. Performance results are then presented for three different temporal-reference-based adaptive beamforming algorithms, namely the Sample Matrix Inversion (SMI),