Third-Generation Systems and Intelligent Wireless Networking: Smart Antennas and Adaptive Modulation

by

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Introduction

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].

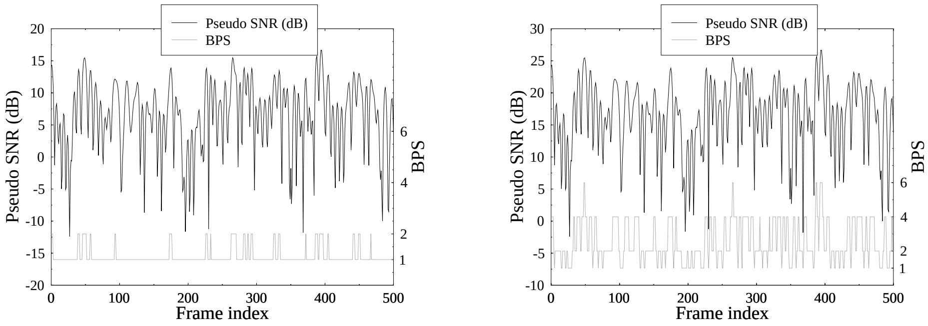
The digital transmission techniques of the Second Generation (2G) mobile radio networks have already improved upon the capacity and voice quality attained by the analogue mobile radio systems of the first generation. However, more efficient techniques allowing multiple users to share the available frequencies are necessary. Classic techniques of supporting a multiplicity of users are frequency, time, polarisation, code or spatial division multiple access [3]. In Frequency Division Multiple 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 time slot, 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 time slot 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 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 time slot by exploiting the spatial selectivity properties offered by adaptive antennas [7]. By contrast, if the desired signal and interferers occupy the same frequency band and time slot, then "temporal filtering" cannot be used for separating the signal from the interference. However, the desired and interfering signal 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, due to using small cells, the more frequently the same frequency is re-used and hence higher teletraffic density per unit area 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 cells, while the Signal-to-Interference Ratio (SIR) can be increased due to the antenna's directionality. The ultimate solution, however, is to use independently steered high gain beams for supporting individual users [3].

Adaptive Quadrature Amplitude Modulation (AQAM) [12, 13] is another technique that is capable of increasing the spectral efficiency that may be achieved. 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 SINR, then a high-order modulation mode may be employed, enabling the exploitation of the temporarily high channel capacity. By contrast, if the channel has a low instantaneous SINR, using a high-order modulation mode would result in an unacceptable Frame Error Ratio (FER), and hence a more robust, but lower throughput modulation mode would be invoked. Hence, adaptive modulation not only combats the effects of a poor quality channel, but also attempts to maximise 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 changing the current modulation mode, i.e. where an alternative AQAM mode must be invoked.

A more explicit representation of the wideband AQAM regime is shown in Figure 1, which displays the variation of the modulation mode with respect to the pseudo SNR at channel SNRs of 10 and 20dB. In these figures, 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. These figures 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 characterise a hostile outdoor environment, where the perceived channel quality was low. This resulted in the utilization of predominantly more robust modulation modes, such as BPSK and 4QAM. Conversely, a less hostile indoor environment is exemplified by Figure 1(b), where the perceived channel quality was high. As a result, the wideband AQAM regime can adapt suitably by invoking higher-order modulation modes, as evidenced by Figure 1(b). Again, this simple example demonstrated that wideband AQAM can be utilized, in order to provide a seamless, near-instantaneous reconfiguration between for example indoor and outdoor environments.



(a) Channel SNR of 10dB

(b) Channel SNR of 20dB

Figure 1: Modulation mode variation with respect to the pseudo SNR evaluated at the output of the channel equaliser of a wideband AQAM modem for transmission over the **TU Rayleigh fading channel**. The BPS throughputs of 1, 2, 4 and 6 represent BPSK, 4QAM, 16QAM and 64QAM, respectively.

This book studies the network capacity gains that may be achieved with the advent of adaptive antenna arrays and adaptive modulation techniques in both FDMA / TDMA and CDMA based mobile cellular networks. The advantages of employing adaptive antennas are multifold, as outlined below.

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] experience in the uplink (UL) and downlink (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 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 higly correlated with the desired signal.

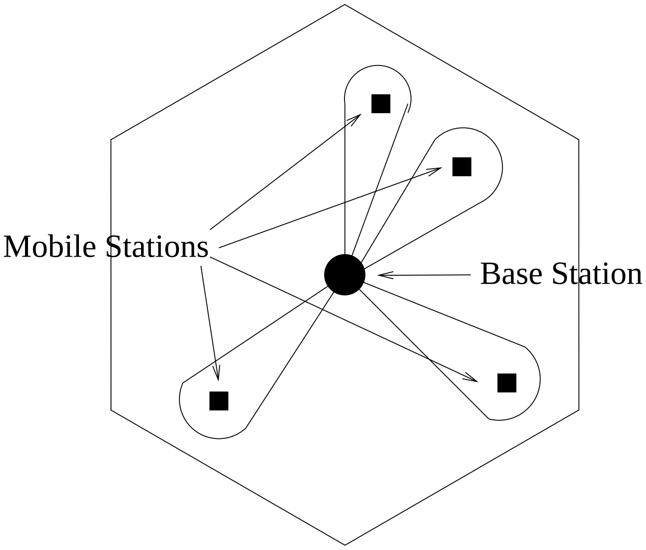


Figure 2: A cell layout showing how an antenna array can support many users on the same carrier frequency and timeslot with the advent of spatial filtering or Space Division Multiple Access (SDMA).

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 quality of service that results from the reduced co-channel interference and reduced multipath fading [18, 19] upon using smart antennae 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.

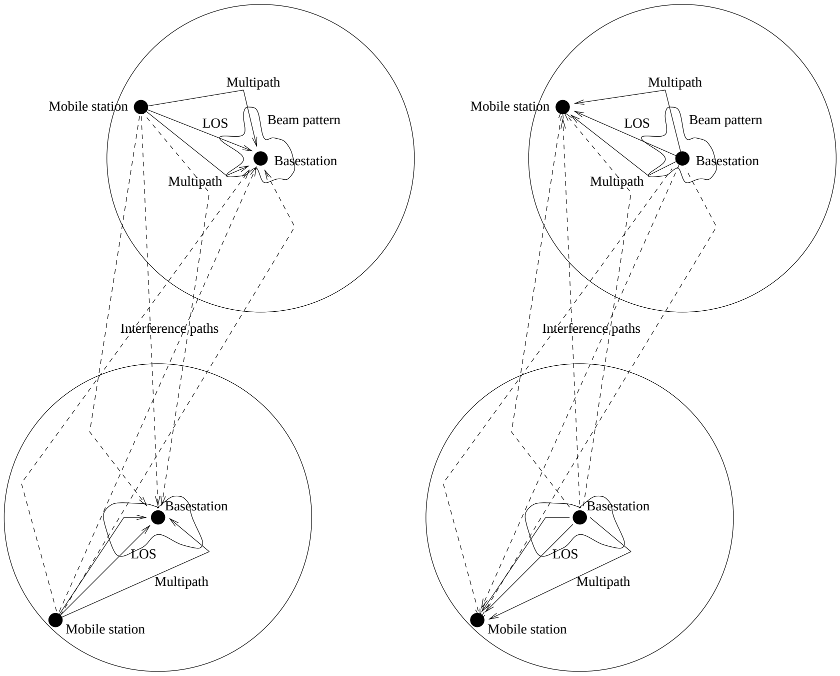
Avoiding Transmission Errors: When the instantaneous channel quality is low, conventional fixed-mode transceivers typically inflict a burst of transmission errors. By contrast, adaptive transceivers avoid this problem by reducing the number of transmitted bits per symbol, or even by disableing transmissions temporarily. The associated throughput loss can be compensated 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 the 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 up-link signals impinging upon the base station's receiver antenna array. A result of the increased number of received up-link 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]. By 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 up- and the downlink, with the multipath components of the desired signal and interference signals clearly illustrated, where the up- and downlink multipath components were assumed to be identical for the sake of simplicity. Naturally, this is not always the case and hence we will investigate the potential performance gains, when the up- and downlink beamforms are determined independently.

The Outline of the Book

- **Chapter 1:** We commence by reviewing the state-of-the-art in near-instantaneously adaptive modulation and introduce the associated principles. We then apply the AQAM philosophy in the context of CDMA as well as OFDM and quantify the service-related benefits of adaptive transceivers in terms of the achievable video quality.

- **Chapter 2:** Following a brief introduction to the principles of CDMA the three most important 3G wireless standards, namely UTRA, IMT 2000 and cdma 2000 are characterised. The range of various transport and physical channels, the



(a) Uplink. **(b)** Downlink.

Figure 3: The multipath environments of both the uplink and downlink, showing the multipath components of the desired signals, the line-of-sight interference and the associated base station antenna array beam patterns.

multiplexing of various services for transmission, the aspects of channel coding are discussed. The various options available for supporting variable-rates and a range quality of service are highlighted. The uplink and downlink modulation and spreading schemes are described and UTRA and IMT 2000 are compared in terms of the various solutions standardised. The chapter is closed with a similar portrayal of the pan-American cdma 2000 system.

- **Chapter 3:** 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), Unconstrained Least Mean Squares (ULMS) and the Normalised Least Mean Squares (NLMS) algorithms.

- **Chapter 4:** A brief summary of possible methods used for modelling the performance of an adaptive antenna array is provided. This is followed by an overview of fixed and dynamic channel allocation. Multipath propagation models are then considered for use in our network simulations. Metrics are then developed for characterising the performance of mobile cellular networks and our results are presented for simulations conducted under Line-Of-Sight (LOS) propagation conditions, both with and without adaptive antennas. Further results are then given for identical networks under multipath propagation conditions, which are then extended to power-controlled scenarios using both fixed and adaptive QAM techniques. These network capacity results were obtained for both "island" type simulation areas, and for an infinite plane, using wraparound techniques.

- **Chapter 5:** This chapter provides a brief description of the 3rd generation mobile cellular network, known as UTRA - the UMTS Terrestrial Radio Access - network, and then presents network capacity results obtained under various propagation conditions, in conjunction with different soft handover threshold metrics. The performance benefits of adaptive antenna arrays are then analysed, both in a non-shadowed environment, and inflicted by log-normal shadow fading having a frequencies of 0.5 Hz and 1.0 Hz . This work was then extended by the invoking of adaptive modulation techniques, which were studied when the channel conditions were impaired by shadow fading.
- **Chapter 6:** Conclusions and further work.

Contributions of the Book

- Providing an introduction to near-instantaneously adaptive modulation invoked in the context of both single- and multi-carrier modulation or OFDM, as well as CDMA.
- Quantifying the service-related benefits of adaptive transceivers in the context of wireless video telephony.
- Providing an overview of the various CDMA based 3G wireless standards.
- Study of the network performance gains using adaptive antenna arrays at the base station in an FDMA / TDMA cellular mobile network [22, 23].
- Study of the network performance gains using adaptive antenna arrays in conjunction with power control at the base station in an FDMA/TDMA cellular mobile network [24, 25].
- Design of a combined power control and adaptive modulation assisted channel allocation algorithm, and characterisation of its performance in an FDMA / TDMA cellular mobile network [25, 26].
- Comparing the performance of various UTRA soft-handover techniques.
- Quantifying the UTRA network capacity under various channel conditions.
- Evaluating the network performance of UTRA with the aid of adaptive antenna arrays.

- Demonstrating the benefits of adaptive modulation in the context of both FDMA / TDMA and CDMA cellular mobile networks.

Our hope is that the book offers you a range of interesting topics in the era of the imminent introduction of 3G wireless networks. We attempted to provide an informative technological roadmap, allowing the reader to quantify the achievable network capacity gains with the advent of introducing more powerful enabling technologies in the phisical layer. Analyzing the associated system design trade-offs in terms of network complexity and network capacity is the basic aims of this book. We aimed for underlining the range of contradictory system design trade-offs in an unbiased fashion, with the motivation of providing you with sufficient information for solving your own particular wireless networking problems. Most of all however we hope that you will find this book an enjoyable and relatively effortless reading, providing you with intellectual stimulation.

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Glossary

AWGN	Additive White Gaussian Noise
BS	A common abbreviation for Base Station
CDMA	Code Division Multiple Access
CMA	Constant Modulus Algorithm
DCS1800	A digital mobile radio system standard, based on GSM, but operates at 1.8GHz at a lower power.
DOA	Direction Of Arrival
FDD	Frequency Division Duplex
GSM	A Pan-European digital mobile radio standard, operating at 900MHz.
HIPERLAN	High Performance Radio Local Area Network
IF	Intermediate Frequency
LMS	Least Mean Square, a stochastic gradient algorithm used in adapting coefficients of a system
MS	A common abbreviation for Mobile Station
MSE	Mean Square Error, a criterion used to optimised the coefficients of a system such that the noise contained in the received signal is minimised.
PDF	Probability Density Function
RF	Radio Frequency
RLS	Recursive Least Square

SDMA	Spatial Division Multiple Access
SINR	Signal to Interference plus Noise ratio, same as signal to noise ratio (SNR) when there is no interference.
SIR	Signal to Interference ratio
SNR	Signal to Noise Ratio, noise energy compared to the signal energy
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunication System

Bibliography

[1] M. Barrett and R. Arnott, "Adaptive antennas for mobile communications," *IEE Electronics & Communications Engineering Journal*, pp. 203–214, August 1994.

[2] S. C. Swales, M. A. Beach, D. J. Edwards, and J. P. McGeehan, "The Performance Enhancement of Multibeam Adaptive Base-Station Antennas for Cellular Land Mobile Radio Systems," *IEEE Transactions on Vehicular Technology*, vol. 39, pp. 56–67, February 1990.

[3] J. Litva and T. Lo, *Digital Beamforming in Wireless Communications.* Artech House, London, 1996.

[4] A. B. Carlson, *Communication Systems.* McGraw-Hill, 1986.

[5] J. G. Proakis, *Digital Communications.* Mc-Graw Hill International Editions, 3 ed., 1995.

[6] L. C. Godara, "Applications of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations," *Proceedings of the IEEE*, vol. 85, pp. 1029–1060, July 1997.

[7] G. V. Tsoulos and M. A. Beach, "Calibration and Linearity issues for an Adaptive Antenna System," in *IEEE Proceedings of Vehicular Technology Conference*, pp. 1597–1600, 1997.

[8] B. D. V. Veen and K. M. Buckley, "Beamforming: A Versatile Approach to Spatial Filtering," *IEEE ASSP Magazine*, pp. 4–24, April 1988.

[9] A. J. Paulraj and B. C. Ng, "Space-Time Modems for Wireless Personal Communications," *IEEE Personal Communications*, pp. 36–48, February 1998.

[10] A. J. Paulraj and E. Lindskog, "Taxonomy of space-time processing for wireless networks," *IEEE Proceedings on Radar, Sonar and Navigation*, vol. 145, pp. 25–31, February 1998.

[11] R. Steele and L. Hanzo, *Mobile Radio Communications.* IEEE Press - John Wiley, 2nd ed., 1999.

[12] W. T. Webb and L. Hanzo, *Modern Quadrature Amplitude Modulation: Principles and Applications for Wireless Communications.* IEEE Press-Pentech Press, 1994. ISBN 0-7273-1701-6.

[13] L. Hanzo, W. T. Webb, and T. Keller, *Single- and Multi-Carrier Quadrature Amplitude Modulation.* John-Wiley, IEEE Press, 2000.

[14] N. Anderson and P. Howard, "Technology and Transceiver Architecture Considerations for Adaptive Antenna Systems," in *Proceedings of ACTS Summit*, pp. 965–970, 1997.

[15] J. Strandell, M. Wennstrom, A. Rydberg, T. Oberg, O. Gladh, L. Rexberg, E. Sandberg, B. V. Andersson, and M. Appelgren, "Experimental Evaluation of an Adaptive Antenna for a TDMA Mobile Telephony System," in *Proceedings of PIMRC*, pp. 79–84, 1997.

[16] J. J. Monot, J. Thibault, P. Chevalier, F. Pipon, S. Mayrargue, and A. Levy, "A fully programmable prototype for the experimentation of the SDMA concept and and use of smart antennas for UMTS and GSM/DCS1800 networks," in *Proceedings of PIMRC*, (Helsinki, Finland), pp. 534–538, September 1997.

[17] M. Mizuno and T. Ohgane, "Application of Adaptive Array Antennas to Radio Communications," *Electronics and Communications in Japan, Part 1*, vol. 77, no. 2, pp. 48–56, 1994.

[18] Y. Ogawa and T. Ohgane, "Adaptive Antennas for Future Mobile Radio," *IEICE Trans. Fundamentals*, vol. E79-A, pp. 961–967, July 1996.

[19] G. V. Tsoulos, M. A. Beach, and S. C. Swales, "On the Sensitivity of the Capacity Enhancement of a TDMA system with Adaptive Multibeam Antennas," in *IEEE VTC Proceedings*, pp. 165–169, 1997.

[20] P. Leth-Espensen, P. E. Mogensen, F. Frederiksen, K. Olesen, and S. L. Larsen, "Performance of Different Combining Algorithms for a GSM System applying Antenna Arrays," in *Proceedings of ACTS Summit*, 1997.

[21] W. Jakes, ed., *Microwave Mobile Communications.* Wiley-Interscience, 1974.

[22] J. S. Blogh, P. J. Cherriman, and L. Hanzo, "Adaptive Beamforming Assisted Dynamic Channel Allocation," in *Proceedings of VTC*, (Houston, USA), pp. 199–203, May 1999.

[23] J. S. Blogh, P. J. Cherriman, and L. Hanzo, "Comparative Study of Dynamic Channel Allocation Algorithms," *IEEE Transactions on Vehicular Technology*, 2001.

[24] J. S. Blogh, P. J. Cherriman, and L. Hanzo, "Dynamic Channel Allocation Using Adaptive Antennas and Power Control," in *Proceedings of ACTS Mobile Communications Summit*, (Sorrento), pp. 943–948, June 1999.

[25] J. S. Blogh, P. J. Cherriman, and L. Hanzo, "Dynamic Channel Allocation Techniques using Adaptive Modulation and Adaptive Antennas," *Accepted for publication in IEEE Journal on Selected Areas in Communications*, 2001.

[26] J. S. Blogh, P. J. Cherriman, and L. Hanzo, "Dynamic Channel Allocation Techniques using Adaptive Modulation and Adaptive Antennas," in *Proceedings of VTC Fall*, (Amsterdam, The Netherlands), pp. 2348–2352, September 1999.

[27] L. Hanzo, "Bandwidth-efficient wireless multimedia communications," *Proceedings of the IEEE*, vol. 86, pp. 1342–1382, July 1998.

[28] S. Nanda, K. Balachandran, and S. Kumar, "Adaptation techniques in wireless packet data services," *IEEE Communications Magazine*, vol. 38, pp. 54–64, January 2000.

[29] L. Hanzo, P. Cherriman, and J. Streit, *Video Compression and Communications over Wireless Channels: From Second to Third Generation Systems and Beyond.* IEEE Press, 2001. (For detailed contents please refer to http://www-mobile.ecs.soton.ac.uk.).

[30] Research and Development Centre for Radio Systems, Japan, *Public Digital Cellular (PDC) Standard, RCR STD-27.*

[31] Telcomm. Industry Association (TIA), Washington, DC, USA, *Dual-mode subscriber equipment — Network equipment compatibility specification, Interim Standard IS-54*, 1989.

[32] Telcomm. Industry Association (TIA), Washington, DC, USA, *Mobile station — Base station compatibility standard for dual-mode wideband spread spectrum cellular system, EIA/TIA Interim Standard IS-95*, 1993.

[33] D. Knisely, S. Kumar, S. Laha, and S. Nanda, "Evolution of wireless data services : IS-95 to cdma2000," *IEEE Communications Magazine*, vol. 36, pp. 140–149, October 1998.

[34] T. Ojanperä and R. Prasad, *Wideband CDMA for Third Generation Mobile Communications.* Artech House, Inc., 1998.

[35] W. Webb and R. Steele, "Variable rate QAM for mobile radio," *IEEE Transactions on Communications*, vol. 43, no. 7, pp. 2223–2230, 1995.

[36] S. Sampei, S. Komaki, and N. Morinaga, "Adaptive Modulation/TDMA scheme for large capacity personal multimedia communications systems," *IEICE Transactions on Communications*, vol. E77-B, pp. 1096–1103, September 1994.

[37] J. M. Torrance and L. Hanzo, "Upper bound performance of adaptive modulation in a slow Rayleigh fading channel," *Electronics Letters*, vol. 32, pp. 718–719, 11 April 1996.

[38] C. Wong and L. Hanzo, "Upper-bound performance of a wideband burst-by-burst adaptive modem," *IEEE Transactions on Communications*, vol. 48, pp. 367–369, March 2000.

[39] J. M. Torrance and L. Hanzo, "Optimisation of switching levels for adaptive modulation in a slow Rayleigh fading channel," *Electronics Letters*, vol. 32, pp. 1167–1169, 20 June 1996.

[40] H. Matsuoka, S. Sampei, N. Morinaga, and Y. Kamio, "Adaptive modulation system with variable coding rate concatenated code for high quality multi-media communications systems," in *Proceedings of IEEE VTC '96* [105], pp. 487–491.

[41] A. J. Goldsmith and S. G. Chua, "Variable Rate Variable Power MQAM for Fading Channels," *IEEE Transactions on Communications*, vol. 45, pp. 1218–1230, October 1997.

[42] S. Otsuki, S. Sampei, and N. Morinaga, "Square-qam adaptive modulation/TDMA/TDD systems using modulation estimation level with walsh function," *IEE Electronics Letters*, vol. 31, pp. 169–171, February 1995.

[43] J. Torrance and L. Hanzo, "Demodulation level selection in adaptive modulation," *Electronics Letters*, vol. 32, pp. 1751–1752, 12 September 1996.

[44] Y. Kamio, S. Sampei, H. Sasaoka, and N. Morinaga, "Performance of modulation-level-control adaptive-modulation under limited transmission delay time for land mobile communications," in *Proceedings of IEEE Vehicular Technology Conference (VTC'95)*, (Chicago, USA), pp. 221–225, IEEE, 15–28 July 1995.

[45] J. M. Torrance and L. Hanzo, "Latency and Networking Aspects of Adaptive Modems over Slow Indoors Rayleigh Fading Channels," *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1237–1251, July 1999.

[46] T. Ue, S. Sampei, and N. Morinaga, "Symbol rate controlled adaptive modulation/TDMA/TDD for wireless personal communication systems," *IEICE Transactions on Communications*, vol. E78-B, pp. 1117–1124, August 1995.

[47] T. Suzuki, S. Sampei, and N. Morinaga, "Space and path diversity combining technique for 10 Mbits/s adaptive modulation/TDMA in wireless communications systems," in *Proceedings of IEEE VTC '96* [105], pp. 1003–1007.

[48] K. Arimochi, S. Sampei, and N. Morinaga, "Adaptive modulation system with discrete power control and predistortion-type non-linear compensation for high spectral efficient and high power efficient wireless communication systems," pp. 472–477.

[49] T. Ikeda, S. Sampei, and N. Morinaga, "TDMA-based adaptive modulation with dynamic channel assignment (AMDCA) for high capacity multi-media microcellular systems," in *Proceedings of IEEE Vehicular Technology Conference*, (Phoenix, USA), pp. 1479–1483, May 1997.

[50] T. Ue, S. Sampei, and N. Morinaga, "Adaptive modulation packet radio communication system using NP-CSMA/TDD scheme," in *Proceedings of IEEE VTC '96* [105], pp. 416–421.

[51] M. Naijoh, S. Sampei, N. Morinaga, and Y. Kamio, "ARQ schemes with adaptive modulation/TDMA/TDD systems for wireless multimedia communication systems," pp. 709–713.

[52] S. Sampei, T. Ue, N. Morinaga, and K. Hamguchi, "Laboratory experimental results of an adaptive modulation TDMA/TDD for wireless multimedia communication systems," pp. 467–471.

[53] J. Torrance and L. Hanzo, "Interference aspects of adaptive modems over slow Rayleigh fading channels," *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1527–1545, September 1999.

[54] C. Berrou and A. Glavieux, "Near optimum error correcting coding and decoding: turbo codes," *IEEE Transactions on Communications*, vol. 44, pp. 1261–1271, October 1996.

[55] J. Cheung and R. Steele, "Soft-decision feedback equalizer for continuous-phase modulated signals in wide-band mobile radio channels," *IEEE Transactions on Communications*, vol. 42, pp. 1628–1638, February/March/April 1994.

[56] M. Yee, T. Liew, and L. Hanzo, "Radial basis function decision feedback equalisation assisted block turbo burst-by-burst adaptive modems," in *Proceedings of VTC '99 Fall*, (Amsterdam, Holland), pp. 1600–1604, 19-22 September 1999.

[57] M. S. Yee, B. L. Yeap, and L. Hanzo, "Radial basis function assisted turbo equalisation," in *Proceedings of IEEE Vehicular Technology Conference*, (Japan, Tokyo), pp. 640–644, IEEE, 15-18 May 2000.

[58] L. Hanzo, F. Somerville, and J. Woodard, "Voice compression and communications: Principles and applications for fixed and wireless channels." 2001 (For detailed contents, please refer to http://www-mobile.ecs.soton.ac.uk.).

[59] ITU-T, *Recommendation H.263: Video coding for low bitrate communication*, March 1996.

[60] "COST 207: Digital land mobile radio communications, final report." Office for Official Publications of the European Communities, 1989. Luxembourg.

[61] A. Klein, R. Pirhonen, J. Skoeld, and R. Suoranta, "FRAMES multiple access mode 1 — wideband TDMA with and without spreading," vol. 1, pp. 37–41.

[62] P. Cherriman, C. Wong, and L. Hanzo, "Turbo- and BCH-coded wide-band burst-by-burst adaptive H.263-assisted wireless video telephony," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 10, pp. 1355–1363, December 2000.

[63] T. Keller and L. Hanzo, "Adaptive multicarrier modulation: A convenient framework for time-frequency processing in wireless communications," *Proceedings of the IEEE*, vol. 88, pp. 611–642, May 2000.

[64] A. Klein and P. Baier, "Linear unbiased data estimation in mobile radio sytems applying CDMA," *IEEE Journal on Selected Areas in Communications*, vol. 11, pp. 1058–1066, September 1993.

[65] K. Gilhousen, I. Jacobs, R. Padovani, A. Viterbi, L. Weaver Jr., and C. Wheatley III, "On the capacity of a cellular CDMA system," *IEEE Transactions on Vehicular Technology*, vol. 40, pp. 303–312, May 1991.

[66] S. Kim, "Adaptive rate and power DS/CDMA communications in fading channels," *IEEE Communications Letters*, vol. 3, pp. 85–87, April 1999.

[67] T. Ottosson and A. Svensson, "On schemes for multirate support in DS-CDMA systems," *Wireless Personal Communications (Kluwer)*, vol. 6, pp. 265–287, March 1998.

[68] S. Ramakrishna and J. Holtzman, "A comparison between single code and multiple code transmission schemes in a CDMA system," pp. 791–795.

[69] M. Saquib and R. Yates, "Decorrelating detectors for a dual rate synchronous DS/CDMAchannel," *Wireless Personal Communications (Kluwer)*, vol. 9, pp. 197–216, May 1999.

[70] A.-L. Johansson and A. Svensson, "Successive interference cancellation schemes in multi-rateDS/CDMA systems," in *Wireless Information Networks (Baltzer)*, pp. 265–279, 1996.

[71] S. Abeta, S. Sampei, and N. Morinaga, "Channel activation with adaptive coding rate and processing gain control for cellular DS/CDMA systems," in *Proceedings of IEEE VTC '96* [105], pp. 1115–1119.

[72] M. Hashimoto, S. Sampei, and N. Morinaga, "Forward and reverse link capacity enhancement of DS/CDMA cellular system using channel activation and soft power control techniques," pp. 246–250.

[73] T. Liew, C. Wong, and L. Hanzo, "Block turbo coded burst-by-burst adaptive modems," in *Proceedings of Microcoll'99, Budapest, Hungary*, pp. 59–62, 21–24 March 1999.

[74] L. Hanzo, P. Cherriman, and J. Streit, *Wireless Video Communications: From Second to Third Generation Systems, WLANs and Beyond.* IEEE Press-John Wiley, 2001. IEEE Press, 2001. (For detailed contents please refer to http://www-mobile.ecs.soton.ac.uk.).

[75] P. Cherriman and L. Hanzo, "Programmable H.263-based wireless video transceivers for interference-limited environments," *IEEE Trans. on Circuits and Systems for Video Technology*, vol. 8, pp. 275–286, June 1998.

[76] E. Kuan and L. Hanzo, "Joint detection CDMA techniques for third-generation transceivers," in *Proceeding of ACTS Mobile Communication Summit '98*, (Rhodes, Greece), pp. 727–732, ACTS, 8–11 June 1998.

[77] V. Tarokh, N. Seshadri, and A. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Transactions on Information Theory*, vol. 44, pp. 744–765, March 1998.

[78] V. Tarokh, A. Naguib, N. Seshadri, and A. Calderbank, "Space-time codes for high data rate wireless communication: Performance criteria in the presence of channel estimation errors, mobility, and multiple paths," *IEEE Transactions on Communications*, vol. 47, pp. 199–207, February 1999.

[79] V. Tarokh, N. Seshadri, and A. Calderbank, "Space-time codes for high data rate wireless communications: Performance criterion and code construction," in *Proc IEEE International Conference on Communications '97*, (Montreal, Canada), pp. 299–303, 1997.

[80] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, pp. 1456–1467, July 1999.

[81] H. Holma and A. Toskala, eds., *WCDMA for UMTS : Radio Access for Third Generation Mobile Communications.* John Wiley & Sons, Ltd., 2000.

[82] "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Spreading and modulation (FDD)." 3G TS 25.213 V3.2.0 (2000-03).

[83] F. Adachi, M. Sawahashi, and K. Okawa, "Tree-structured Generation of Orthogonal Spreading Codes with Different Lengths for Forward Link of DS-CDMA Mobile," *Electronics Letters*, vol. 33, no. 1, pp. 27–28, 1997.

[84] "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Physical layer procedures (FDD)." 3G TS 25.214 V3.2.0 (2000-03).

[85] S. Verdú, *Multiuser Detection.* Cambridge University Press, 1998.

[86] A. D. Whalen, *Detection of signals in noise.* Academic Press, 1971.

[87] W. T. Webb and L. Hanzo, *Modern Quadrature Amplitude Modulation : Principles and Applications for Fixed and Wireless Channels.* John Wiley and IEEE Press, 1994.

[88] M. Dell'Anna and A. H. Aghvami, "Performance of optimum and sub-optimum combining at the antenna array of a W-CDMA system," *IEEE Journal on Selected Areas in Communications*, pp. 2123–2137, December 1999.

[89] R. L. Pickholtz, L. B. Milstein, and D. L. Schilling, "Spread spectrum for mobile communications," *IEEE Transactions on Vehicular Technology*, vol. 40, pp. 313–322, May 1991.

[90] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, and C. E. Wheatley, "On the capacity of a cellular CDMA system design," *IEEE Transactions on Vehicular Technology*, vol. 40, pp. 303–312, May 1991.

[91] L. Wang and A. H. Aghvami, "Optimal power allocation based on QoS balance for a multi-rate packet CDMA system with multi-media traffic," in *Proceedings of Globecom*, (Rio de Janeiro, Brazil), pp. 2778–2782, December 1999.

[92] D. Koulakiotis and A. H. Aghvami, "Data detection techniques for DS/CDMA mobile systems: A review," *IEEE Personal Communications*, pp. 24–34, June 2000.

[93] P. J. Cherriman, E. L. Kuan, and L. Hanzo, "Burst-by-burst adaptive joint-detection CDMA/H.263 based video telephony," in *Proceedings of the ACTS Mobile Communications Summit, Sorrento, Italy*, pp. 715–720, June 1999.

[94] J. Laiho-Steffens, A. Wacker, and P. Aikio, "The Impact of the Radio Network Planning and Site Configuration on the WCDMA Network Capacity and Quality of Service," in *IEEE Proceedings of Vehicular Technology Conference*, (Tokyo, Japan), pp. 1006–1010, 2000.

[95] R. D. Kimmo Hiltunen, "WCDMA Downlink Capacity Estimation," in *IEEE Proceedings of Vehicular Technology Conference*, (Tokyo, Japan), pp. 992–996, 2000.

[96] K. Sipilä, Z.-C. Honkasalo, J. Laiho-Steffens, and A. Wacker, "Estimation of Capacity and Required Transmission Power of WCDMA Downlink Based on a Downlink Pole Equation," in *IEEE Proceedings of Vehicular Technology Conference*, (Tokyo, Japan), pp. 1002–1005, 2000.

[97] M. L. Cheng and J. I. Chuang, "Performance evaluation of distributed measurement-based dynamic channel assignment in local wireless communications," *IEEE JSAC*, vol. 14, pp. 698–710, May 1996.

[98] "GSM 06.90: Digital cellular telecommunications system (Phase 2+)." Adaptive Multi-Rate (AMR) speech transcoding, version 7.0.0, Release 1998.

[99] S. Bruhn, E. Ekudden, and K. Hellwig, "Adaptive Multi-Rate: A new speech service for GSM and beyond," in *Proceedings of 3rd ITG Conference on Source and Channel Coding*, (Technical Univ. Munich, Germany), pp. 319–324, 17th-19th, January 2000.

[100] S. Bruhn, P. Blocher, K. Hellwig, and J. Sjoberg, "Concepts and Solutions for Link Adaptation and Inband Signalling for the GSM AMR Speech Coding Standard," in *Proceedings of VTC*, (Houston, Texas, USA), 16-20 May 1999.

[101] T. Ojanperä and R. Prasad, ed., *Wideband CDMA for 3rd Generation Mobile Communications*. Artech House Publishers, 1998.

[102] R. Owen, P. Jones, S. Dehgan, and D. Lister, "Uplink WCDMA capacity and range as a function of inter-to-intra cell interference: theory and practice," in *IEEE Proceedings of Vehicular Technology Conference*, vol. 1, (Tokyo, Japan), pp. 298–303, 2000.

[103] B. G. Evans and K. Baughan, "Visions of 4G," *IEE Electronics and Communication Engineering Journal*, vol. 12, pp. 293–303, December 2000.

[104] W. Tuttlebee, ed., *Cordless telecommunications in Europe : the evolution of personal communications*. London: Springer-Verlag, 1990. ISBN 3540196331.

[105] IEEE, *Proceedings of IEEE VTC '96*, (Atlanta, GA, USA), 1996.