1 INTRODUCTION

"Imagination is more important than knowledge, for knowledge is limited while imagination embraces the entire world."

— Albert Einstein

During the past ten years, there has been an explosive growth of personal and mobile wireless services whose ultimate goal is to support universal personal and multimedia services without regards to mobility and location. These future services are intended to provide image, video and local area network applications requiring high-speed data transmission that may be more than 1000 times faster than present systems [1]. Current development trends in telecommunications are driven by user requirements, which include access to a diverse range of services for anyone, anywhere, anytime and at the lowest possible cost. In an ideal world, this would ultimately lead to one worldwide mobile solution, using one radio-access network and one single core network. Physical limits imposed by the mobile radio channel cause performance degradation and make it very difficult to achieve high bit rates at low error rates over time dispersive wireless channels.

In order to understand the importance of this thesis, the contributions are sketched against the background of an ever increasing user population that is placing increasingly stringent demands on existing and planned communication networks for high quality flexible services.

Smart antennas have recently been proposed for wireless communications [2, 3, 4, 5]. The use of multiple element antenna arrays is an attractive solution because they can mitigate the effects of multipath fading as well as suppress co-channel interference, thereby significantly improving system performance. These antenna arrays may be employed either at the transmitter or the receiver. In a cellular radio system, it is generally most practical to employ an antenna array at the base station rather than at the mobile terminals. Then, in transmitting from the mobile to the base station (uplink channel), receiver diversity is achieved through a multiple receive antenna array, while in transmitting from the base station to the mobiles (downlink channel), transmit diversity is achieved through a multiple transmit antenna array. To further improve system performance, both spatial (multiple antennas) and temporal (multipath combining and coding) processing can be combined so that both the time and space or angular domains can be efficiently exploited. This joint space-time processing can be adopted at both the base stations and mobile stations to improve the system performance and capacity by orders in magnitude [6, 7].

In this thesis, the focus is on coded transmit diversity and its achievable performance when used in cellular CDMA systems. Transmitter diversity has traditionally been viewed as more difficult to exploit than receiver diversity, in part because of the challenging signal design problem: the transmitter is permitted to generate a different signal at each antenna element. The addition of coding complicates the signal design problem, but increases the transmitter diversity degrees of freedom, and also the potential of optimal space-time coded diversity gain.

In this chapter, a brief introduction into some of the newest developments in mobile communications is presented. Specific emphasis is placed on the infra-structural evolution of second generation mobile communication networks to third generation mobile communication networks. Then, the goals and specific contributions of this thesis are listed in Section 1.2. The basic definitions and operating principles of antenna arrays and coded space-time processing for spread spectrum code division multiple access (CDMA) are presented in Section 1.3, as a basis for the work covered in this thesis. Finally, the organization of this thesis is described in Section 1.4.

1.1 OVERVIEW

1.1.1 From Second Generation to Third Generation

Mobile communications at the beginning of the 21th century is characterized by a diverse set of applications using many incompatible standards. In order for today's mobile communications to become truly personal communications in this century, it will be necessary to consolidate the standards and applications into a single unifying framework. The eventual goal is to define a global third generation mobile radio standard called the Future Public Land Mobile Telecommunications System (FPLMTS).

The success of the European second generation system, GSM, has created a mass market for mobile communications, reaching high terminal penetration in global markets. At the end of June 1998, there were 293 members of the GSM memorandum of understanding (MoU) association from 120 different countries worldwide. There are currently 278 GSM networks in operation serving 95 million subscribers, and these are still growing. A further boost to the mass market will be the introduction of multi-mode multi-band terminals, such as GSM/DCS 1800/PCS 1900, GSM/satellite and many other handset combinations. The penetration for mobile communications in developed countries is expected to rise to 50%-80% within the time frame from the introduction of Universal Mobile Telecommunication System (UMTS) [8, 9]. The UMTS system is only one of many new third generation systems being developed around the world, and serves as illustration for our current discussion.

UMTS cannot be developed as a completely isolated network with minimal interface and service interconnection to existing networks. Both UMTS and existing networks will need to develop along parallel, even convergent paths, if service transparency is to be achieved to any degree. This would then, in the end, allow UMTS services to be supported, although at different levels of functionality, across all networks. Another important requirement for seamless operation of the two standards is GSM-UMTS hand-over in both directions. Restrictions on the applicability of hand-over may be necessary for particular services and when services are different between the systems. This will require modifications of existing GSM specifications. GSM networks also need to be protected from unwanted side-effects caused by functions needed to support cross handovers.

1.1.2 Universal Mobile Telecommunications System

UMTS wideband code division multiple access (WCDMA) is one of the major new third generation (3G) mobile communication systems being developed within the FPLMTS framework. It represents a substantial advance over existing mobile communications systems. Above all else it is being designed with flexibility for users, network operators and service developers in mind and embodies many new and different concepts and technologies. UMTS seeks to build on and extend the capabilities of today's mobile, cordless and satellite technologies by providing increased capacity, data capability and a far greater range of services using an innovative radio access scheme and an enhanced, evolving core network.

As the demand for user data rates increases in the long term, UMTS will be developed to support even higher data rates, perhaps one or two orders of magnitude greater (provided appropriate spectrum is allocated). In later phases of UMTS development there will be a convergence with even higher data rate systems, known as broadband radio access networks (BRAN), using mobile wireless local area network (LAN) technologies (microwave or infrared) providing data rates of, for example, 155 Mbit/s in indoor environments. Figure 1.1 illustrates the mobility and coverage of UMTS compared with GSM and BRAN.

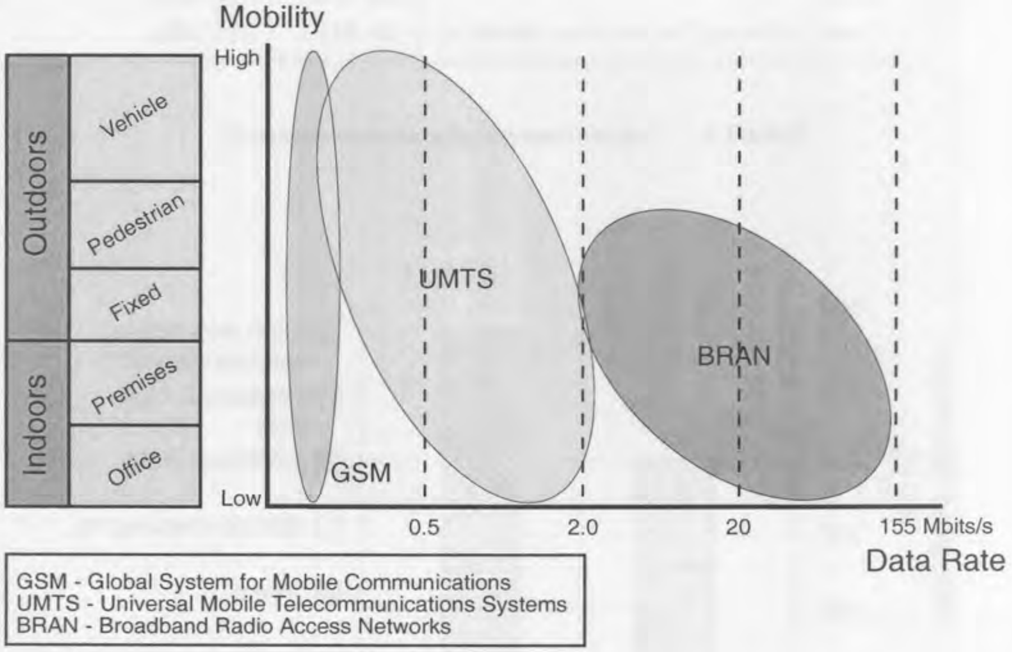

Figure 1.1. UMTS coverage versus information data bit rate.

In practical implementations of UMTS, some users may be unable to access the highest data rates at all times. For example, the physical constraint of radio propagation and the economics of operating a network will mean that the system services might only support lower data rates in remote or heavily congested areas. Therefore, in order to ensure that the subscriber is always able to use his or her terminal, services will be adaptive to different data rate availability and other quality of service (QoS) parameters. For this reason UMTS is also being designed to offer data rate on demand, where the network reacts adaptively to the user's demands, the customer's profile and the current status of the network. The use of packet-oriented transport protocols is being studied so that UMTS can enhance these abilities. Together, the combination of packet data and data rate on demand will remove technical barriers for the user and make operation of the system much cheaper – there will be no worries about how and when to connect to the network.

Table 1.1 and Figure 1.2 show the projected required frequencies per service in typical busy hours for the years 2005 and 2010. The conclusion is that roughly 580 MHz will be required in the year 2010. The requirement includes the bands currently designated for second generation (2G) systems, and the bands designated as core bands for UMTS, plus new spectrum resources fully and flexibly exploited. It is envisaged that the increase in penetration after 2010 will not be significant [8, 10]. The use of services requiring wider bandwidth, however, is expected to increase, which will lead to increasing spectrum demand.

Year	2005	2010
High interactive multimedia[1]	22 MHz	82 MHz
Medium and high multimedia[2]	113 MHz	241 MHz
Switched data	12 MHz	9 MHz
Simple messaging	2 MHz	2 MHz
Voice	220 MHz	220 MHz
Total	369 MHz[3]	554 MHz[4]
Total (allowing for spectrum division)	406 MHz	582 MHz

Table 1.1. Future terrestrial spectrum requirements [8].

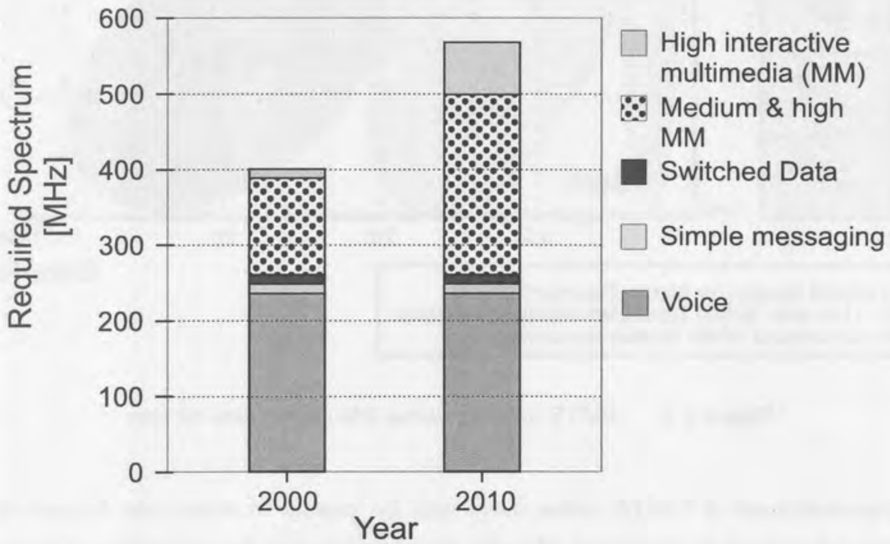

Figure 1.2. Required spectrum for terrestrial UMTS services (including second generation services) [8].

1.1.3 Third Generation and Beyond

In order to ensure that the FPLMTS vision is sustained in the long term, its capabilities will need to be progressively increased by the addition of new technologies. A selection of these are detailed below.

1.1.3.1 Re-configurable Terminals. Future mobile terminals will have to exist in a world of multiple standards – both 2G and those of other members of the FPLMTS family. Also, standards themselves are expected to evolve. In order to provide universal coverage, seamless roaming and non-standardized services, some of the elements of the radio interface (e.g. channel coder, modulator, demodulator, etc.) will no longer have fixed parameters, they will rather take the form of a "toolbox" whereby key parameters can be selected or negotiated to match the requirements of the local radio channel. In addition to the ability to adapt to different standards described above, downloadable terminals will enable network operators to distribute new communications software over the air in order to improve the terminals' performance in the network or to fix minor problems.

1.1.3.2 Application and Service Download. In using today's multimedia terminals (for example PCs), users have learned to accept the idea that the capabilities of the terminal can be modified over time by software downloading. It is now commonplace for a user to download a new "plug in" (for example a video or audio codec) to access new types of content. The introduction of multimedia services in UMTS will take this concept into the mobile domain.

1.1.3.3 Broadband Satellite Systems. Several broadband satellite systems are also planned for deployment in the post 2002 time frame (designed to offer data rates beyond 2 Mbit/s and into the Gigabits domain). Some of these systems may offer compatibility with UMTS service concepts using satellite frequency allocations in the 20/30 GHz range. The requirements of the terminal equipment and higher power consumption will necessitate larger transportable or fixed terminals.

1.1.3.4 Space-time Techniques. As will be discussed throughout this thesis, space-time techniques are a key way to enhance the capability of mobile communication services in the long term, and are currently regarded by many within the wireless communications industry as a core system component in future-generation mobile networks. For example, the current UMTS standard already provides for antenna array use. The pilot bits available in the dedicated physical channels ensure that space-time technology can be introduced in the future. As an example of a space-time processing technique, antenna arrays react intelligently to the received radio signal, continually modifying their parameters to optimize the transmitted and received signal. More detail concerning these techniques are given in Section 1.3.

1.2 GOALS OF THIS THESIS AND STATEMENT OF ORIGINALITY

Clearly radio technologies are no longer confined to serving the needs of mobile or rural telecommunications users. In fact, it can be said that radio technology has been liberated and that it is today viewed as a viable alternative to access technologies such as fiber and copper. This liberation of radio technology from its traditional role as a mobile or rural access system is further exemplified by Figure 1.1. UMTS solutions, for instance, can be applied to many different mobility and service provision scenarios, with other high speed radio access technologies like wireless local area networks and mobile broadband systems extending the applicability of radio based access solutions to almost any conceivable scenario.

In order to understand the importance of this thesis, the goals and contributions are sketched against the background of an ever increasing user population that is placing increasingly stringent demands on existing and planned communication networks for high quality, flexible services. Of particular importance in this thesis, will be those CDMA based solutions for the mobile sector and the new performance analysis issues that need to be addressed as a result of the introduction of heterogeneous services and service environments into a single, mobile cellular access network. Furthermore, novel applications of transmit antenna diversity techniques to mobile cellular access networks aimed at increasing the efficiency of such networks will be considered.

1.2.1 Thesis Goals

Against the background of the rapid evolution of mobile communication systems in the areas of service provision and capacity enhancement described above and the role of smart antenna concepts therein, this thesis has the following goals:

- To establish a general spatial/temporal channel model for use in the evaluation of coded space-time processing concepts applied to CDMA networks.
- To analyze the performance of uncoded cellular CDMA systems incorporating space-time techniques using analytical methods in a number of realistic application scenarios.
- To design, implement and evaluate coding strategies for incorporation into the space-time CDMA systems. This objective can be broken down into the following items:
  - Space-time coding systems when considering multiple transmit antennas for the downlink.
  - Coded space-time systems when considering multiple receive antennas for the uplink.
- To establish the performance of coded space-time CDMA cellular networks under realistic scenarios.

1.2.2 Statement of Originality

This thesis examines the topic of combined diversity and turbo coding systems in CDMA. Several novel results and techniques are developed which allow significant performance improvements under a range of conditions in cellular CDMA systems.

The main contributions are summarized below.

- Turbo encoding and its applicability to transmit diversity and receive beamforming/diversity scenarios for cellular CDMA is investigated and illustrated.
- New analytical models are developed to provide a simple mechanism of evaluating the performance of the existing space-time coding proposals. These analytical models facilitate a direct comparison of various techniques.
- The field of knowledge is extended by introduction of a particular class of layered space time codes for CDMA, namely turbo transmit diversity (TTD).
- Novel TTD schemes are designed and their performance analyzed. These are:
  - Parallel concatenated TTD (PCTTD).
  - Serial concatenated TTD (SCTTD).
  - Super-orthogonal TTD (SOTTD).
- The work of previous authors in the field of space-time trellis codes is extended. The relationship between multiple trellis coded modulation (MTCM) and good space-time code design techniques is shown.

- New analytical models are developed for determining the performance of space-time trellis codes based on MTCM techniques. New metrics for measuring space time code quality and for examining the relative "goodness" of existing space-time codes are derived.

- The relationship between turbo coded space-time turbo codes in receive diversity and directional antenna (beamforming) systems is examined.

Details about the organization of this thesis are presented in Section 1.4.

1.3 CODED SPACE-TIME PROCESSING FOR CELLULAR CDMA

Theoretically, the most effective technique to mitigate flat fading in a wireless channel is transmitter power control. In addition, if the channel multipath conditions as experienced by the receiver are known at the transmitter, the transmitter can pre-distort the signal in order to compensate for the distortion introduced by the channel at the receiver. Other effective techniques are time, frequency and space diversity. When possible, wireless communication systems should be designed to encompass all forms of available diversity to ensure adequate performance [11].

From a practical point-of-view, space diversity reception in the uplink is one of the most effective and, hence, widely applied techniques for mitigating the effects of multipath fading. The classical approach is to use multiple antennae at the receiver and perform combining or selection and switching in order to improve the received signal quality. The major problem with the receive diversity approach at the mobile terminal, is cost, size and power. As a result, antenna diversity techniques have almost exclusively been applied to the base stations. In this thesis, the use of multiple transmit/receive antennas at the base station is considered, when combined with advanced forward error correcting codes to increase system capacity of cellular CDMA communication for both the uplink and downlink.

The reasoning behind the use of space-time processing techniques (which include smart antennas as a special case) is the optimization of the cellular spectral efficiency of the network. This is realized by implementing more than one antenna element to optimally transmit or receive signals by using both temporal and spatial signal processing techniques in the transceiver. Well known techniques such as antenna sectorization (spatial signal processing), diversity combining (spatial and temporal signal processing) and beamforming arrays (spatial and temporal signal processing) are considered to be examples of space-time processing. In fact, all antenna array systems can be considered to be space-time processors.

1.3.1 Channel Coding and CDMA

CDMA communications are interference-limited systems, due to the presence of self and mutual interference signals at the receiver antenna. This is because all users communicate simultaneously in the same frequency band [12, 13]. The received signal suffers multipath fading created by the reflections and diffraction by many obstacles, such as buildings and hills located between the mobile. Multiple access interference (MAI) is often produced which significantly reduces the link capacity. Thus, advanced techniques to counteract these impairments are indispensable in order to minimise MAI. Forward error correction (FEC) coding can be regarded as a time diversity technique when it is combined with interleaving of sufficient depth. Thus, FEC aims to correct errors caused by noise and interference in the CDMA communication environment.

Channel coding is an extremely complex topic to which entire books are dedicated. The reader is referred to Lin and Costello [14] or Clark and Cain [15] for detailed introductory discussions on FEC coding, and to

Viterbi and Omura [16], Petersen and Weldon [17], Gallager [18], Berlekamp [19, 20] and Biglieri *et al.* [21] for advanced discussions of both information theoretic and algebraic foundations of channel coding.

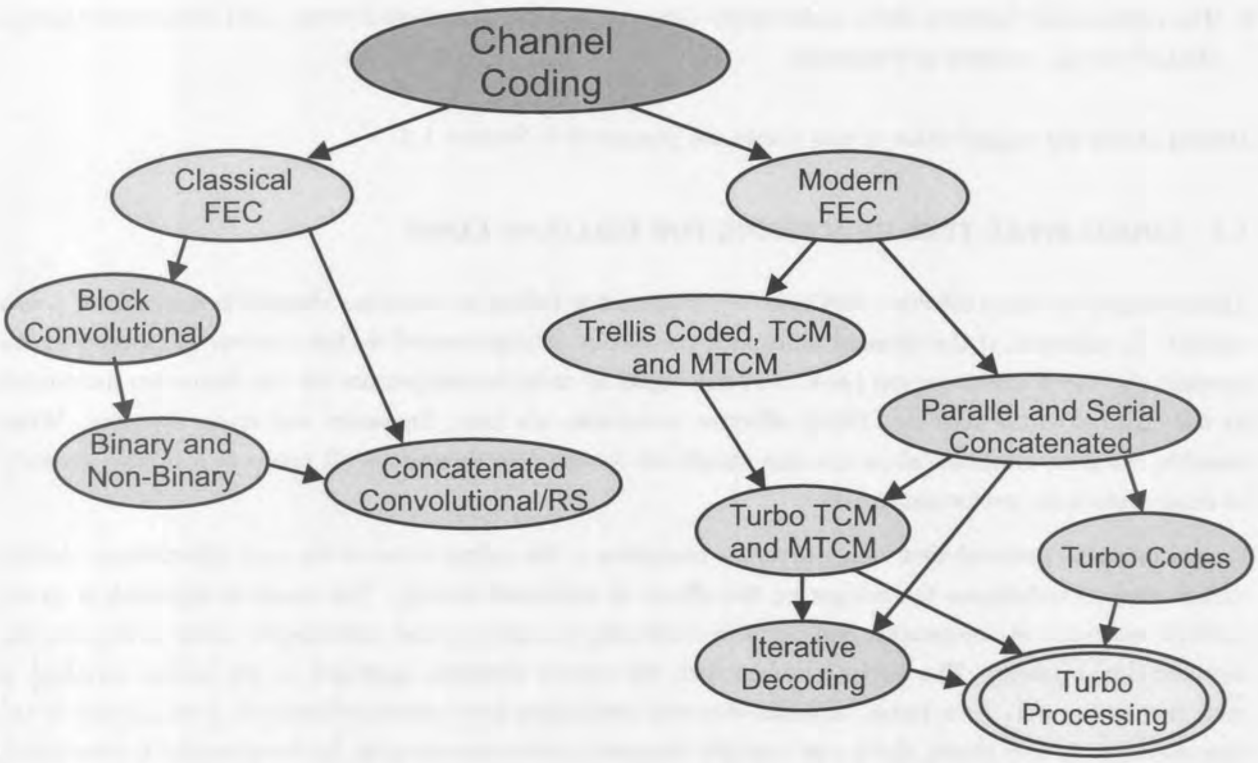

Figure 1.3. Classification of channel coding techniques.

As shown in Figure 1.3, channel coding techniques can broadly be classified as:

- Classical FEC coding, including
  - Binary (e.g., Hamming and Reed-Muller) and non-binary (e.g., Reed-Solomon) block codes,
  - Convolutional codes, and
  - Concatenated block and convolutional codes.
- Modern FEC coding, including
  - Trellis coding, encapsulating both trellis coded modulation (TCM) and multiple trellis coded modulation (MTCM), and
  - Parallel (turbo) and serial concatenated convolutional and block codes with iterative decoding, and
  - Turbo trellis coded modulation.

Turbo codes and its trellis coded variants are the parallel concatenation of two recursive systematic convolutional (RSC) codes separated by an interleaver and decoded using iterative decoding techniques. The discussion here is confined to the more general concepts of turbo processing. In Chapter 4, a more detailed discussion on turbo codes and their application to CDMA communications will be presented.

The Viterbi algorithm was introduced in 1967 as a computationally efficient method for performing maximum likelihood (ML) decoding of convolutional codes [22]. Since then, it has found numerous other applications including maximum likelihood sequence estimation (MLSE) equalizers [23], trellis-coded modulation [24], and multiuser detection [25, 26, 27, 28]. Along these lines, it was soon recognized that the iterative method of decoding turbo codes was also suitable for many other applications, and could be incorporated as a design methodology for advanced receiver design. Examples of sub-systems include source decoding [29], symbol detection [30], equalizers [31] and multiuser detectors [32, 33, 34]. Also, in line with the thesis goals, combinations with multiple transmit and receive antennas.

Communication receivers typically consist of a cascade of signal processing intensive subsystems, each optimized to perform a single task. In a "conventional" receiver, the interface between subsystems involves the passing of bits, or hard-decisions, down the stages of the chain. Whenever hard-decisions are made, information is lost and becomes unavailable to subsequent stages. Additionally, stages at the beginning of the processing chain do not benefit from information derived by stages further down the chain. The interface between stages can be greatly improved by employing the same strategy used to decode turbo codes. In [30] the term "turbo processing" was coined to describe the general strategy of iterative feedback decoding or detection. The latter processing forms the basis for the space-time turbo coded processing techniques for the downlink. These techniques are covered in detail in Chapters 5 and 6.

1.3.1.1 Coded Cellular CDMA. It is well known that CDMA systems exhibit maximum capacity potential when combined with FEC coding [13, 35, 36, 37, 38]. In fact, most FEC systems, especially those with low code rates, expand bandwidth and can be viewed as spreading systems. The positive trade-off between greater distance properties of lower rate codes and increased cross-correlation effects (due to shorter sequence length) is fundamental to the success of coded CDMA. From information theory it is known that the maximum theoretical CDMA capacity can only be achieved by employing very low rate FEC codes utilizing the entire bandwidth, without further spreading by the multiple access sequence [38, 39, 40, 41].

Viterbi [35, 38] has proposed the use of orthogonal convolutional codes as low rate code extensions for code-spreading CDMA. Recently, two new classes of low rate codes with improved performance have been proposed. Pehkonen *et al.* [42, 43] proposed a coding scheme that combines super-orthogonal turbo codes (SOTCs) with super-orthogonal convolutional codes (SOCCs) [38]. A different approach was taken by Frenger *et al.* [40, 41], where a class of nested rate-compatible convolutional codes (RCCC), with maximum free distance (MFD), was derived.

In [44], performance gains achieved in a RAKE based CDMA system with convolutional versus trellis coding were reported. Codes were constructed over an MPSK signal set by taking a standard Ungerboeck type code for MPSK modulation and multiplied by a binary pseudo-noise sequence, thereby spreading the signal over a large bandwidth. It was reported that this approach did not yield a performance advantage over standard convolutional codes, with the conclusion that it is better to exploit the low distance properties of low rate convolutional codes as opposed to using higher order modulation schemes for efficient signalling.

A different approach to trellis coded CDMA was investigated by Woerner *et al.* [45]. In this approach the trellis code is constructed over the set of possible signature sequences rather than over some $2D$ signal constellation. Instead of expanding the number of signal points in the $2D$ constellation, the signal points were expanded over a set of orthogonal spreading sequences. A carefully designed trellis then allows only certain combinations of sequences that have a large total minimum distance. By increasing the number of sequences, the actual minimum distances between sequences have been decreased. The trellis code compensates for this decrease by increasing the minimum distance of the code above that of the uncoded system.

For non-optimum multiuser receivers, such as the MF or RAKE, coding gain comes at the cost of increased MAI level. A limitation to the use of low rate coding comes when the spreading is reduced to such a level that the MAI does not appear Gaussian anymore. By using more powerful codes than those used by Boudreau *et al.* [44], the issue of spreading versus coding can be more adequately addressed. For a finite effective code rate (and hence a finite spreading ratio), the level of MAI, under AWGN equal power conditions, is fixed. If the MAI was truly Gaussian in nature, turbo codes should perform in a similar way as if applied to an AWGN channel. For a RAKE receiver with perfect channel estimation, the soft input turbo code will perform equally well in an AWGN and a fading channel. The power of turbo coding approaching the Shannon bound in narrow band systems, implies that almost optimum performance should be achievable with coded CDMA systems under similar signalling conditions.

1.3.2 Space-time Processing Techniques

The introduction of spatial aspects into the cellular problem through the innovative use of antennas now offers new possibilities to extend the receiver algorithms mentioned above. Specifically, the use of multiple antennas at both the transmitter and the receiver adds a new dimension to the CDMA receiver problem as it allows for the improved separation of users' signals. Through the use of space-time processing techniques, the levels of MAI and fading a receiver has to cope with can be significantly reduced, thereby increasing the capacity of the overall system. In the latter parts of this thesis, the above mentioned receiver structures, used in conjunction with coded space-time processing, are discussed in detail.

With this in mind, the purpose of space-time processing systems should become clearer. Essentially, space-time processing techniques provide an integrated approach to fight channel impairments on two fronts. Firstly, by introducing diversity into the system to minimize the effects of fading on the received signal and secondly by adaptively changing the radiation pattern of the antenna system to minimize the total MAI seen by the receiver. Whereas both techniques are well known, the power of space-time processing lies therein that the basic principles of beamforming and diversity are incorporated in the overall system design. Thus, space-time processing is defined as:

Space-time processing is the minimization of fading and MAI through the integrated use of multiple antennas, advanced signal processing techniques, advanced receiver structures and forward error correction.

Based on this definition, the main aim of space-time techniques for mobile systems is to maintain an acceptable level of error performance and, hence, to maximize the signal-to-interference and noise ratio (SINR) for each user in the system.

Combinations of implicit (coded) and external (i.e., multiple transmit/receive antennae) for space-time diversity and beamforming processing can be used to improve both the downlink and uplink QoS of CDMA cellular communications. As will be shown in this thesis, it is important to note that the overall system gains that can be achieved with these space-time coded systems, depend heavily on the error correction strategy employed.

Following along the lines of the discussion above, the general definition of space-time processing is extended to incorporate coding. In the context of the thesis, two concepts need to be defined, namely space-time coded processing (or simple space-time coding), and coded space-time processing. These are defined as:

Space-time coded processing refers to the combined use of adaptive antenna arrays and forward error correction coding in the downlink of a cellular network to maximize the combined space-time diversity/beamforming and coding gain.

Coded space-time processing refers to the use of adaptive antenna arrays, followed by a forward error correction coding strategy in the uplink of a cellular network to make maximum use of the available diversity/beamforming gain.

Thus, in space-time coding the signal processing involved with the use of multiple transmit antennas and coding are combined to provide a so called space-time coding gain in the downlink. For coded space-time processing systems multiple receive antennas are considered combined with coding in the uplink. For both the uplink and downlink channel diversity, beamforming or combined diversity/beamforming techniques may be considered.

In general, space-time processing techniques can be classified according to Figure 1.4. Diversity techniques require a number of signal transmission paths, called diversity branches, that carry the same information but have, ideally, uncorrelated multipath fading, and a circuit to combine the received signals or to select one of them. This definition of diversity differs from beamforming where it is normally assumed that the signals arriving at the antenna array are perfectly correlated. Whenever the signals on the various antenna elements are not perfectly correlated, the beamforming pattern is influenced in a detrimental way. At some point, due to a lack of correlation, the beam pattern will revert back to an omni-directional pattern. Lack of correlation is normally induced by the environment through which the received signal is propagated and also due to the spacing of the antenna elements. Whenever the correlation, ρ_{ij}, between branch i and j, is less than perfect, that is $\rho_{ij} < 1$, there will be some diversity gain present in the system. Diversity combining is different from antenna array processing and beamforming in that it combines signals at baseband or at a intermediate frequency to increase the signal level without affecting the individual antenna pattern. Beamforming techniques, on the other hand, exploit the differential phase between different antennas to modify the antenna pattern of the whole array. In this arrangement, once the signals are combined, the whole of the array has a single antenna pattern.

1.3.2.1 Transmit Diversity. For narrowband TDMA many techniques have been proposed to provide transmit diversity. These techniques can broadly be categorized as

- space-space transmit diversity (polarized antennas are often used to realize space-space transmit diversity),
- space-frequency transmit diversity and space-phase transmit diversity (the introduction of frequency offsets [46] and phase-sweeping [47, 48], to convert a frequency non-selective channel into a frequency selective channel is a technique used to realize such a transmit diversity scheme), and
- space-time transmit diversity (examples are FIR pulse shaping techniques imposing intentional intersymbol interference (ISI) [49, 50, 51, 52, 53], delay diversity [54, 55, 56], and space-time antenna-hopping (also known as round-robin antenna selection [57]) diversity schemes.)

Many of these techniques can easily be extended to CDMA. A general classification of transmit diversity techniques, for TDMA and CDMA, can be summarized as follows:

Transmit Diversity with Feedback [58, 59].
In these schemes, implicit or explicit (closed loop) information is fed from the receiver to the transmitter in order to configure the transmit diversity structure. Winters [58, 60] considered switched diversity with

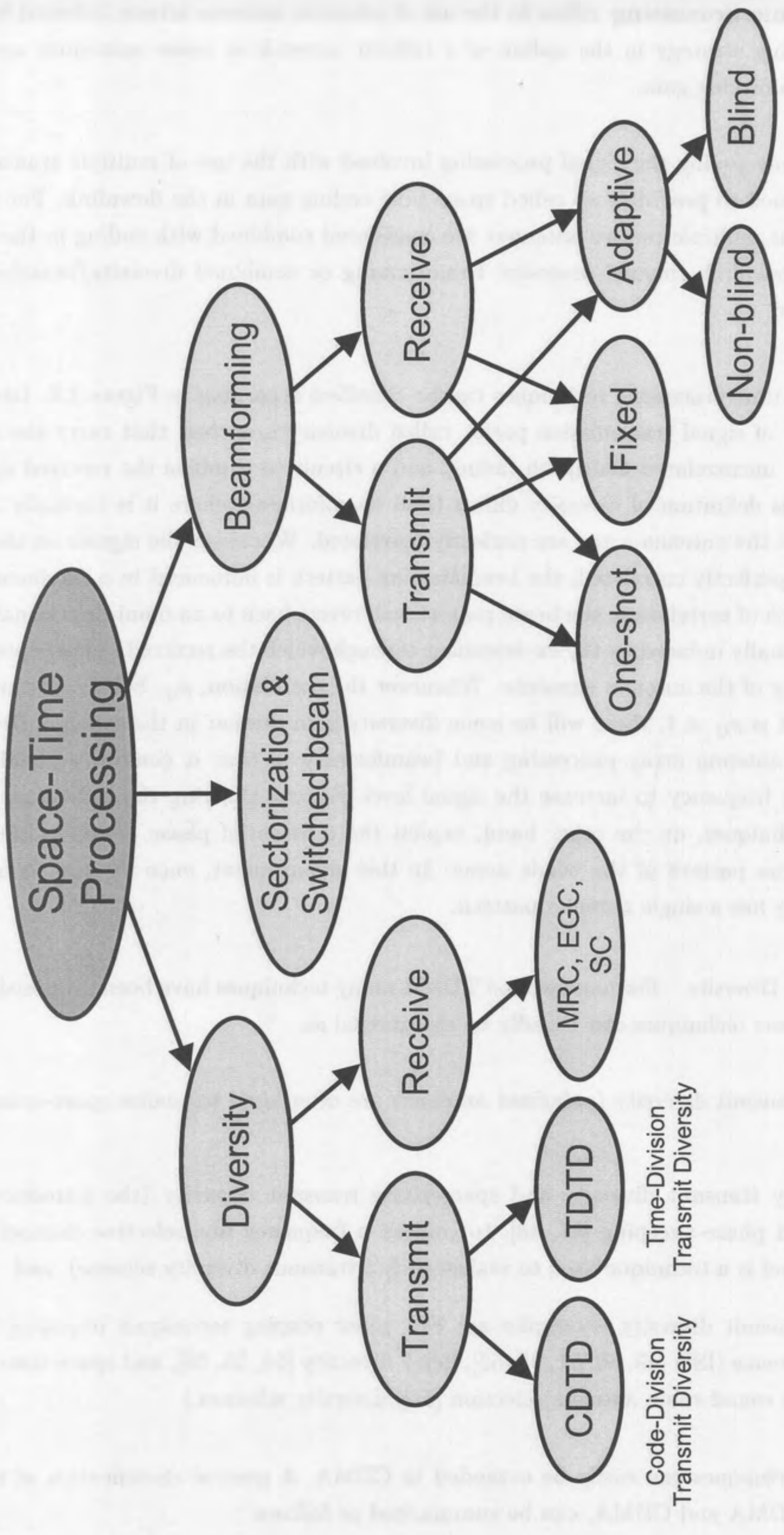

Figure 1.4. Classification of space-time processing techniques.

feedback while Raleigh et al. [59] considered spatio-temporal-frequency water pouring, a technique based on channel feedback response. These techniques are limited in practice by vehicle movements and/or interference which cause a mismatch between the state of the channel perceived by the transmitter and that perceived by the receiver.

Transmit Diversity with Training Information [49, 50, 54, 61].
Linear processing at the transmitter is used to distribute encoded and control (e.g. transmitter power) information to the antenna sub-sequences. Feed-forward or training information is utilized to estimate the link from the transmitter to the receiver. The first scheme of this type was proposed by Wittneben [50], which includes the delay diversity scheme presented by Seshadri *et al.* [54] as a special case. Lu *et al.* [61] has considered a technique where channel reciprocity was assumed by assigning the same antenna weights to the transmitter and receiver via implicit (open loop) feedback.

Hybrid Feedback/Training Transmit Diversity.
In practice, the information update rate is slow, and channel reciprocity cannot be guaranteed because of vehicle movement and/or interference. Here, the feedback and training estimates are combined to compensate for the channel response at both the transmitter and receiver. In this way the best features of both open and closed loop channel state estimation are combined.

Blind Transmit Diversity [47, 48, 54, 62, 63].
No feedback or feed-forward information is required. Instead, blind transmit diversity exploits the use of multiple transmit antennas combined with channel coding to achieve diversity. An example of this approach is to combine phase sweeping transmitter diversity [47] with channel coding [48]. Here a small frequency offset is introduced on one of the antennas to create fast fading. Another scheme is to encode the information by a channel code and then to transmit the code symbols using different antennas in an orthogonal manner. This can be achieved by either considering frequency multiplexing [62], or time multiplexing [54]. Also in the case of CDMA, orthogonal spreading sequences can be assigned to the different transmitting antennas [63]. When appropriate channel coding is employed, it is possible to relax the orthogonality requirement, with the benefit of achieving diversity and coding gain.

Two promising transmit diversity techniques well suited to CDMA are code-division transmit diversity (CDTD) and time-division transmit diversity (TDTD). These techniques will be covered in detail in Chapter 3.

1.3.2.2 Receive Diversity. With receive diversity systems, the fact that the signals arriving at different locations fade at different rates, are therefore utilized [64]. A system employing a receive diversity combiner uses signals induced on various antennas placed a few wavelengths apart at different locations and combines these signals in one of many ways [65]. These combining techniques can broadly be categorized as follows:

Selection Combining (SC) [66]. This is the simplest receive diversity technique, that simply selects the best of the available diversity branches. The selection may be based upon the power of the desired signal, the total power, or the SINR available at each antenna.

Maximal Ratio Combining (MRC) [67, 68, 69, 70, 71]. In this method the signals from all of the diversity branches are weighted according to their individual SNRs and then summed. Here, the individual signals must be co-phased before being summed to produce an output SNR equal to the sum of the individual SNRs. This technique gives the best statistical reduction of fading of any known linear diversity combiner.

Equal Gain Combining (EGC) [66]. The equal gain combiner adjusts the phases of the desired signals and combines them in-phase after equal weighting. This allows the receiver to exploit signals that are simultaneously received on each branch. The possibility of producing an acceptable signal from a number of unacceptable inputs is still retained, and performance is only marginally inferior to MRC and superior to SC.

1.3.2.3 Beamforming. Receive beamforming refers to the use of adaptive antenna arrays in the uplink of a cellular network to focus the antenna beam on a specific user, thereby increasing the antenna gain in the direction of the user and suppressing transmissions received from interfering users.

In the case of TDMA and FDMA systems the beamforming system may use pencil antenna beams [72] to focus on the active users, whereas in CDMA systems, the system can increase the SNR in the uplink by introducing nulls in the antenna pattern in the direction of strong interfering signals.

In a manner similar to receive beamforming, transmit beamforming can be used in the downlink of a cellular system to focus all the energy radiated by the base station onto a single user or cluster of users [73]. Transmit beamforming reduces the interference experienced by mobile communication systems in the downlink by concentrating all radiated electromagnetic energy in the direction of a user or group of users, avoiding geographical areas where no users are active.

Transmit and receive beamforming techniques can broadly be classified as follows [74].

Fixed Beamforming [75, 76, 77]. The first application of antenna arrays in beamforming is that of fixed beamforming networks.

One-shot Beamforming [76, 77]. A slightly more general case of a fixed beamforming network would be a one-shot beamformer. A one-shot beamformer is defined as a beamforming array where an optimal radiation pattern or antenna weights are determined using a single operation. Such beamforming techniques are also known as statistically optimal techniques as they determine a weight vector which is optimum in some statistical sense. Specifically, the weight vector is determined by minimizing a cost function. Minimizing the cost function will maximize the signal quality at the output of the beamformer. One of the most popular techniques is the minimum mean square error (MMSE) algorithm, which is widely used.

Adaptive Beamforming [77, 78, 79, 80, 81]. There are several reasons why it is not desirable to solve the optimum weight vector directly. Since the mobile environment varies with time, the solution of the weight vector must be updated periodically. Typically, the change in the channel from one adaptation cycle to the next will be small. Also, since the data required to estimate the weight vector is noisy, it is desirable to use the current weight vector to determine the next weight vector. This would result in a smoothing of the weight vector reducing the effect of noise. When a training sequence is used in the adaptation process, the beamforming method is known as non-blind beamforming, while the solution of the weight vector, without the use of training sequences, is known as blind beamforming.

Because the uplink of a cellular network is, in general, the capacity limiting factor, it might seem that receive diversity and beamforming systems will yield greater capacity advantages than the transmit diversity and beamforming systems. However, the increased downlink quality afforded by transmit space-time techniques may lead to fewer dropped calls during handovers (because of the better signal quality estimates available to the mobile), increasing the overall QoS. In addition, the downlink of a cellular system in future wireless systems will also be a limiting aspect due to for example downloading of large files to a mobile terminal from a server and the limited possibilities to implement space-time signal processing techniques at mobile receivers.

It is therefore clear that both transmit and receive space-time processing techniques are of great importance in wireless communication systems.

1.3.2.4 **Multi-beam and Switched-beam Antennas.** In addition to diversity and beamforming systems, smart antenna techniques such as multi-beam and switched-beam antennas can also be used to increase the capacity of CDMA systems. In [82], experimental test results show that a multi-beam antenna array with fixed beam azimuths can increase the capacity of a CDMA system compared to a system using sectorized antennas. Furthermore, in [83, 84] it is shown that switched-beam antennas can both increase the capacity of a CDMA systems, as well as extend the radio coverage by increasing the carrier-to-interference ratio (CIR).

1.3.3 Space-time Processing Performance

This thesis will consider the performance of the cellular system in terms of parameters such as bit error rate, rather than the operation and performance of specific algorithms for the control of the antenna radiation pattern. In this regard, many algorithms exist for the adaptation of the weights associated with each radiating element (on a global or peruser basis) and for the combining of signals received on radiating elements.

The analysis of the bit error probability (BEP) and outage performance of CDMA systems have received much attention in literature. The analysis of basic asynchronous CDMA systems in Additive White Gaussian Noise (AWGN) channels using a Gaussian approximation of the interfering signal is presented in [85, 86]. In [87, 88, 89], upper and lower bounds on the average error probability for CDMA systems in AWGN channels are presented. The evaluation of CDMA systems was extended in [90] to include multipath fading channels, where the fading coefficients were either Rayleigh or Rician distributed random variables. Additionally, a detailed analysis of the performance of a CDMA system over Nakagami channels is presented in [91]. Performance analysis methodologies that utilize more accurate descriptions of specifically the MAI present in the cellular network are presented in [92], with extensions to the modeling of the MAI presented in [93, 94, 95].

All of the above mentioned performance analysis methodologies considered only basic CDMA systems with no smart antenna systems included. The basic smart antenna systems that are most often analyzed are receive diversity systems. In [67, 68], optimum diversity combining and equalization techniques for TDMA mobile radio systems are evaluated. In these references, it is clearly shown that diversity techniques can significantly increase the performance of mobile radio systems. These results are extended in [69, 96, 97] where it is shown that diversity matched filters and combining techniques such as MRC, EGC and SC can significantly increase the performance of mobile radio systems over Nakagami channels. The same is true for frequency selective fading channels, as is indicated in [98] and [99] where it is shown that space diversity techniques may improve system performance by as much as 10 dB. The system gains described for TDMA systems are also realizable in CDMA systems. In [100], the performance of a microcellular CDMA system over slow and fast Rician fading radio channels with forward error correction coding and diversity is presented. In this paper, it is clearly shown that increasing the order of the diversity system increases the system capacity, a result which is confirmed in [64, 101, 102, 103]. In addition to diversity systems, smart antenna techniques such as multibeam and switchedbeam antennas can also be used to increase the capacity of CDMA systems. In [82], experimental test results show that a multibeam antenna array with fixedbeam azimuths can increase the capacity of a CDMA system compared to a system using sectorized antennas.

The promise of increased system capacity through the use of multiple transmit and receive antenna techniques such as diversity and beamforming have lead to the detailed analysis of such systems. In [104, 105, 106], the application of antenna arrays to TDMA systems such as GSM is described. These results are extended to CDMA system in a number of papers. For example, in [78, 107, 108, 109] interference cancellation systems using antenna arrays are described as examples of CDMA systems using antenna arrays to increase system performance by limiting interference. This theme is central to a number of applications of antenna arrays in limiting MAI. In [110] for instance, a linear receiver for direct sequence spread spectrum multiple access systems with antenna arrays and blind adaptation is described.

Various other system analysis approaches to determine the gains afforded by smart antenna techniques in CDMA systems can also be found in literature. In [111, 112], simulation and experimental results are used to show the gains that can be achieved through the use of smart antennas as beamforming arrays. However, as was stated in the goals of this thesis, an analytic solution to this problem is required. Various approaches to obtaining analytical solutions have also been published. In [113], the system gain is determined based on the approach of calculating the increase in signal to interference and noise ratio (SINR) that can be achieved by transmit and receive beamforming techniques. Such an approach can yield a first order approximation of system gains, but does not take a number of physical realities, such as the distribution of users and fast/slow fading, into account. In [70, 114], the analysis is extended to include aspects such as multipath scattering, fading and, to a lesser extent, user distribution. In [115], these effects are analyzed for CDMA systems without antenna arrays and where the fading parameters are arbitrarily chosen as opposed to being calculated based on the physical scenario in which the cellular system is deployed. In [116, 117, 118], the performance of adaptive antenna array systems has been treated were the effects of fading correlation, fading and antenna array configurations are discussed respectively. In [116], a power based approach as described above is used to determine the effect of fading correlation on diversity communication systems.

1.3.4 Advantages of Space-time Processing

As has been discussed in the foregoing sections and in [119, 120, 121, 122, 123, 124, 125], (coded) space-time techniques have the ability to improve the performance of a mobile communication system in a number of ways. Specific advantages of space-time techniques are that they yield:

- Increased capacity (spectrum efficiency) by increasing the number of active users for a given BEP quality.
- Reduction of co-channel interference to improve QoS and/or increase the frequency re-use factor. This point is especially important in CDMA-based systems in which the system capacity is interference limited.
- Reduction in delay spread and fading. By beamforming and diversity techniques, the SINR of the system can be improved in a fading environment. Related to this is the reduction of the effect of angular spreading of the received signal due to scatterers around the mobile (which is close to the ground) by narrow beams being formed on the arriving signals.
- Reduction in outage probability. Outage probability is the probability of a channel being inoperative due to an increased error rate. For example, by reducing interference using space-time techniques, the outage probability can be reduced.
- Increase in transmission efficiency. Due to the high directivity and gain of the space-time system, base station range may be extended, and a mobile may be able to transmit using less power resulting in longer battery life.

- Reduction in hand-off rate. When the capacity of a cellular system is exceeded, cell splitting is used to create new cells, each with its own base station and new frequency assignment, with increased hand-off as a result. Hand-off may be reduced by space-time processors which can create independent beams.
- Improved positioning accuracy by applying multi-beam antenna arrays.
- Reduction in cost, complexity and potential network architecture simplification. There is no doubt that dynamic hand-off, dynamic channel assignment, and dynamic nulling (all features of space-time systems) require more complexity. However, careful consideration should also be given to the overall improvement of system reliability, QoS, etc. when comparing space-time systems to conventional systems.

While antenna arrays provide many advantages, these must be offset against cost and complexity factors. A number of important points to be considered are

- hardware and software requirements increase as the number of antenna elements increases; and
- in practical situations, the antenna array performance may be adversely affected by channel modeling errors, calibration errors, phase drift and noise which is correlated between antennas.

1.4 THESIS ORGANIZATION

In covering the vast topic of space-time processing, this thesis concentrates mainly on three aspects, namely the space-time channel and system models, space-time coded processing for the downlink channel, and coded space-time processing for the uplink.

- In this chapter, an introduction into some of the newest developments in mobile communications is presented. Specific emphasis is placed on the evolution of second generation mobile communication networks to third generation mobile communication networks. A literature survey of forward error correcting codes and space-time processing techniques is presented as a basis for the work presented in this thesis.
- In Chapters 2 to 3, extensive background information on channel impairments and space-time channel and system models are presented. Together these chapters provide the necessary background information required to understand specific space-time processing techniques. The two main smart antenna techniques covered are adaptive beamforming systems, transmit and receive diversity systems, as well as the derivation of the BEP performance of these techniques in cellular environments.

Up to this point, uncoded space-time processing systems have been treated.

- Chapter 4 presents a detailed discussion of the channel coding techniques. Specifically, detailed discussion of convolutional, turbo and TCM FEC are presented. Also, the performance of convolutional and turbo coding for CDMA is analyzed and, as a means of comparison, results on the AWGN channel are presented.

Given the presented material on space-time processing and FEC coding, the following three chapters focus on the combination of the latter techniques to maximize the coding and spatial diversity/beamforming gains on offer.

- In Chapter 5, the thesis introduces layered space-time coding techniques to improve the downlink capacity.

- Chapter 6 considers extensions of the layered space-time turbo coding techniques to turbo transmit diversity techniques and turbo processing.
- In Chapter 7 the layered space-time coding concepts are extended to include trellis coding.
- To improve the uplink system performance and capacity, Chapter 8 concentrates on coded space-time receive diversity, beamforming, and combined diversity and beamforming systems.

In Chapter 9, the concluding chapter, the major results and conclusions of the thesis are presented.

Notes

1. High speed data rates, symmetric and reasonably continuous transmission and minimum delays.
2. Moderate data rates, medium to large files, asymmetric and bursty transmission and tolerance to a range of delays.
3. Already identified spectrum is 395 MHz (70 MHz GSM+150 MHz GSM 1800 + 20 MHz DECT +155 MHz terrestrial UMTS).
4. Trunking inefficiency and guard-bands must be allowed for, due to multiple operators and public/private and service category segmentation. This is assumed to improve from 10% in 2005 to 5% in 2010.

2 SPATIAL/TEMPORAL CHANNEL MODEL

The gain offered by space-time processing relies on many parameters, some of which are beyond the control of the design engineer, but which should be modeled accurately when analyzing such systems. Specifically four main areas of influence can be identified, namely: (i) the propagation path of the signal, (ii) temporal fading, (iii) the scattering environment and, (iv) the angular distribution of subscribers. These factors influence the system performance and careful attention should be given to the different aspects for optimal system design [126]. For this reason a thorough understanding of the various aspects influencing space-time performance is needed.

2.1 SPACE-TIME PROCESSING PERFORMANCE ISSUES

When realistic channel models of a mobile communication system are available, efficient signal processing schemes can be devised to improve system performance, and accurate system analysis can also be performed to predict system capacity and performance. In general, models describe parameters such as received signal strength, power delay profiles and Doppler spectra, which are important for the analysis of systems with omni-directional antennas. Of high importance in space-time systems, is knowledge of the direction of arrival (DOA) of the received signals, which is not available from conventional models. In this chapter, important effects are described such as multipath fading, and models for the scattering surrounding the mobile and base station. It is of importance to note that, due to the difference in angular dispersion at the mobile and base station, the propagation characteristics in the uplink and downlink might be different (channel non-reciprocity), and this is of significance in space-time based system performance analysis. The presented channel model will be used in later chapters to evaluate the performance of space-time CDMA systems under a variety of conditions.

2.1.1 Propagation Path

The modeling of the propagation path needs to take into account a number of effects. These include

- Path (propagation) loss;
- Shadowing (The particular scattering environment (i.e. trees, buildings) along a path at a given distance will be different for every path, causing variations with respect to the nominal value given by the path loss model. Some paths will suffer increased loss, while others will be less obstructed and have an increased signal strength. This phenomenon is called shadowing or slow fading and exhibits log-normal fading statistics.);
- Number of multipath components and the distribution of their envelopes (These effects are a result of the local scattering environment around the mobile and/or base station);
- Temporal fading (Due to its fundamental importance in a mobile environment, this effect is described in detail in Section 2.1.2, with emphasis on a space-time fading environment); and
- Correlation (Multipath components generated by a single area of local scatterers may show considerable correlation, with the correlation depending heavily on assumptions made concerning the spatial distribution of local scattering elements. Correlation is a very important concept in space-time systems since it influences the antenna pattern in beamforming (see Section 3.3.1.1) and the amount of diversity gain achievable in the system. The effect of correlation is considered in detail in Section 3.3.1.1, after the discussion of appropriate channel models for space-time systems).

The above mentioned propagation characteristics influence mainly the performance of the beamforming algorithm used, as well as the performance of the combining algorithm used in the case of space-time systems relying on both beam steering and diversity techniques. Most beamforming algorithms used assume that the signals arriving at each element of the array are highly correlated (ρ_{ij} >0.8) [127]. However, this assumption depends heavily on the composition of the local scattering area surrounding the mobile.

2.1.1.1 Path Loss. If a wireless channel's propagating characteristics are not specified, it is usually inferred that the signal attenuation versus distance behaves as if propagation takes place over ideal free-space. The model of free space treats the region between the transmitting and receiving antennas as being free of all objects that might absorb or reflect RF energy. It is further assumed that, within this region, the atmosphere behaves as a perfectly uniform and non-absorbing medium. Furthermore, the earth is treated as being infinitely far away from the propagating signal. In this idealized free-space model, the attenuation of RF energy behaves according to an inverse-square law.

2.1.2 Temporal Fading

Based on experimental evidence, the cause of fading can be attributed to large-scale fading and/or small-scale fading. Large-scale fading (or shadowing) has path loss as a result with effects as described in Section 2.1.1. Small-scale fading manifests itself in two mechanisms, namely signal dispersion (time-spreading of the signal) and time-variant behavior of the channel. Due to motion between the transmitter and the receiver the channel is time-variant as a result of the propagation path changing. The rate of change of these propagation conditions accounts for the rapidness of the fading (rate of change of the fading impairments). Small-scale fading is generally statistically described by either a Rayleigh [128, 129], Rician [129, 130] or Nakagami-m [130, 131, 132] distribution. The model choice depends mainly on the operating environment of the communication system. If the multiple reflective paths are large in number and there is no line of sight (LOS) signal component, the envelope of the received signal is traditionally statistically described by a Rayleigh probability density function. When there is a dominant non-fading signal component present, such as a LOS propagation path, the small-scale fading envelope is described by a Rician pdf. In addition to the attractive mathematical properties of the Nakagami-m fading model, it has also been shown in [133, 134] that the Nakagami model can be used to accurately describe the fading behavior of multipath signals and the varying physical scattering processes. The distribution of these multipath signal parameters is dependent on the type of environment (i.e., macro-, micro- or pico cell).

2.1.3 Scattering Environment

The distribution of the DOA of multipath signals is often assumed to be uniform over $(0, 2\pi]$ [135, 136]. To determine the performance of a space-time system, channel models that include the effect of the DOA need to be constructed. A critical aspect that determines the DOA at either the base station or the mobile, is the scattering environment around the transmitter and receiver.

For a detailed discussion of spatial scatterer models, the text by Ertel *et al.* [137] may be consulted. Two typical scattering models commonly used are the circular disk of scatterers model (CDSM) [138], and the Gaussian scatterer (GS) model [139]. The CDSM is the "classical" spatial model, while the GS model is more realistic in certain environments. In this section the CDSM originally proposed by Jakes [138] and used in Lee [140] is presented.

2.1.3.1 CDSM DOA [116, 138, 140, 141]. Making extensive use of the results by Van Rheeder *et al.* [141], the DOA pdf at the base station is derived here for the CDSM shown in Figure 2.1.

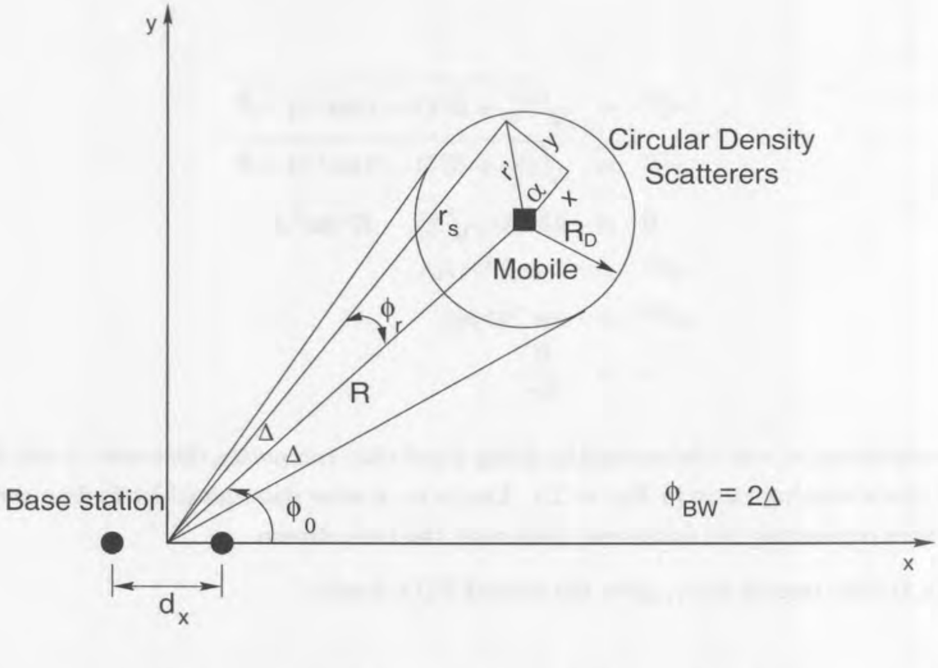

Figure 2.1. Cartesian geometry of circular disk of scatterers model.

If the mobile is located at the co-ordinates $(0, 0)$, then the pdf of the location of scatterers around the mobile is given by

$$p_{X,Y}(x,y) = \begin{cases} \frac{1}{\pi R_D^2} & , x^2+y^2 \le R_D^2 \\ 0 & , \text{elsewhere} \end{cases} . \tag{2.1}$$

Finding the joint density $p_{R_s,\Phi}(r_s,\phi)$ requires a transformation of the random variables (X,Y) into the random variables (R_s,Φ) via

$$p_{R_s,\Phi}(r_s,\phi) = | J | \, p_{X,Y}(x,y)|_{x=r_s \cos\phi - R, y=r_s \sin\phi} , \tag{2.2}$$

where $\phi = 90^o - \phi_0$.

In (2.2), J is the Jacobian of the transformation, computed as

$$J = \begin{vmatrix} \frac{\partial(r_s \cos\phi - R)}{\partial r_s} & \frac{\partial(r_s \sin\phi)}{\partial r_s} \\ \frac{\partial(r_s \cos\phi - R)}{\partial \phi} & \frac{\partial(r_s \sin\phi)}{\partial\phi} \end{vmatrix} = r_s. \tag{2.3}$$

Substituting (2.1) and (2.3) into (2.2) yields the joint density of R_s and Φ

$$p_{R_s,\Phi}(r_s,\phi) = \begin{cases} \frac{r_s}{\pi R_D^2} & , r_s^{(1)} \le r_s \le r_s^{(2)}, \phi^{(1)} \le \phi \le \phi^{(2)} \\ 0 & , \text{otherwise} \end{cases} , \tag{2.4}$$

where

$$\begin{aligned} r_s^{(1)} &= \sqrt{R_D^2 + R^2(1-2\sin^2\phi) - \mathcal{B}} \\ r_s^{(2)} &= \sqrt{R_D^2 + R^2(1-2\sin^2\phi) + \mathcal{B}} \\ \mathcal{B} &= 2R\cos\phi\sqrt{R_D^2 - R^2\sin^2\phi} \\ \phi^{(1)} &= -\sin^{-1}(1/\upsilon) \\ \phi^{(2)} &= \sin^{-1}(1/\upsilon) \\ \upsilon &= \frac{R}{R_D}. \end{aligned} \tag{2.5}$$

Limits on the parameter r_s were determined by fixing ϕ and then computing the points at which the resulting line intersect the scattering circle in Figure 2.1. Limits on ϕ were determined by finding the angles of the two tangent lines connecting the scattering circle with the base station.

Integrating (2.4) with respect to r_s, gives the desired DOA density

$$p_{\Phi,\nu}(\phi,\nu) = \begin{cases} \frac{1}{2\pi}\left(\upsilon\cos\phi + \sqrt{1-\upsilon^2\sin^2\phi}\right)^2 & , 0 \le \phi \le 2\pi, 0 \le \upsilon \le 1 \\ \frac{2}{\pi}\,\upsilon\cos\phi\sqrt{1-\upsilon^2\sin^2\phi} & , \phi^{(1)} \le \phi \le \phi^{(2)};\ \upsilon > 1 \\ 0 & , \text{otherwise.} \end{cases} . \tag{2.6}$$

Note that this result is valid for $\upsilon > 1$ and $0 \leq \upsilon \leq 1$, i.e., when the base station is located outside the scattering circle and when the base station is located inside the scattering circle, respectively.

Figure 2.2 depicts $p_{\Phi,\nu}(\phi, \nu)$ as a function of both ϕ and υ. From this figure, the following observations can be made. For large υ, the situation where the mobile terminal is far from the base station, and all the scatterers are close to the mobile, the pdf approaches an "impulse-like" density. Conversely, for small υ, the situation where the mobile is close to the base station and the scattering circle is large (non line of sight (NLOS) propagation), the pdf approaches a uniformly distributed density. Using (2.6) and setting υ equal to zero, the latter uniform DOA density is calculated as $1/2\pi, \forall\phi$.

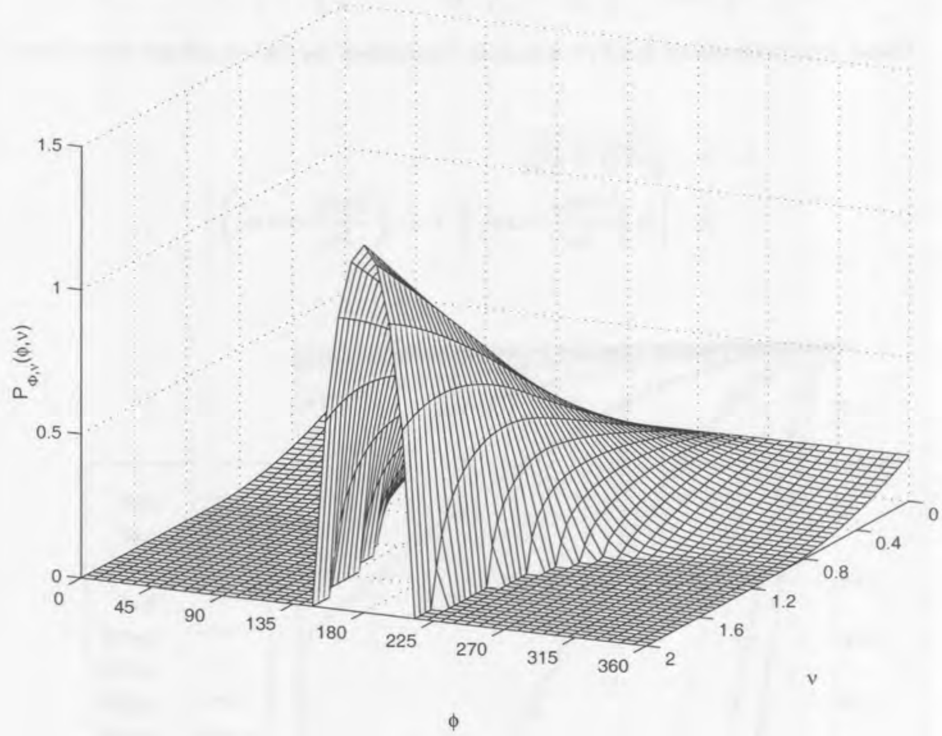

Figure 2.2. DOA as a function of ϕ and υ.

2.1.3.2 CDSM Correlation [141]. In the CDSM it is assumed that all signals arrive at the base station within $\pm\Delta$ of the angle ϕ_0, and that the ith received signal path is uniformly distributed with height $1/2\Delta$. Using the results of Lee [142], the fading correlation between two antenna elements, spaced d_x apart, can be written as two components R_{xx} and R_{xy}

$$R_{xx} = \int_{-\pi/2+\phi_0}^{+\pi/2+\phi_0} \cos[\,2\pi(d_x/\lambda)\sin\,\phi\,]\; p_\Phi(\phi)\; d\phi \tag{2.7}$$

$$R_{xy} = \int_{-\pi/2+\phi}^{+\pi/2+\phi_0} \sin[\,2\pi(d_x/\lambda)\sin\,\phi\,]\; p_\Phi(\phi)\; d\phi. \tag{2.8}$$

where R_{xx} denotes the correlation of the real components of the signal received at the two antennas, and R_{xy} denotes the correlation of the real component of the signal arriving at the one antenna element and the imaginary component arriving at the other antenna element.

From (2.6) with ν constant, the density $p_\Phi(\phi)$ is used to derive R_{xx} and R_{xy} as series expansions of integer order Bessel functions. Substituting (2.6) into (2.7) and (2.8), and using geometric substitutions and some numerical analysis the correlation of fading approximations is found to be [141]

$$R_{xx} \approxeq \left[J_0\left(\frac{2\pi d_x}{\lambda \upsilon}\cos\phi_0\right) + J_2\left(\frac{2\pi d_x}{\lambda \upsilon}\cos\phi_0\right)\right] \cos\left(\frac{2\pi d_x}{\lambda}\sin\phi_0\right), \tag{2.9}$$

and

$$R_{xy} \approxeq \left[J_0\left(\frac{2\pi d_x}{\lambda \upsilon}\cos\phi_0\right) + J_2\left(\frac{2\pi d_x}{\lambda \upsilon}\cos\phi_0\right)\right] \sin\left(\frac{2\pi d_x}{\lambda}\sin\phi_0\right), \tag{2.10}$$

where $\upsilon >> 1$. These approximations lead to a simple expression for the envelope correlation

$$\begin{aligned} \rho &= \sqrt{R_{xx}^2 + R_{xy}^2} \\ &\approxeq \left| J_0\left(\frac{2\pi d_x}{\lambda \upsilon}\cos\phi_0\right) + J_2\left(\frac{2\pi d_x}{\lambda \upsilon}\cos\phi_0\right)\right|. \end{aligned} \tag{2.11}$$

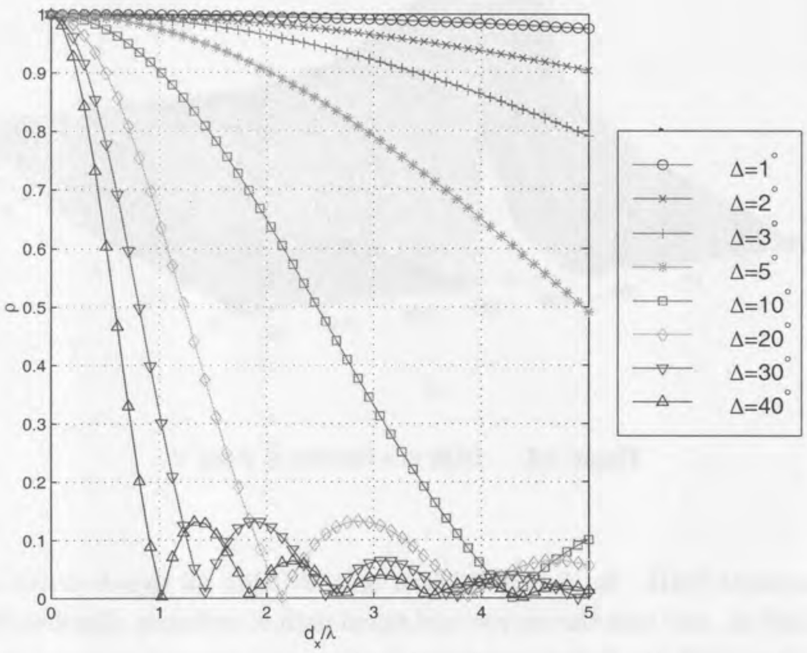

Figure 2.3. CDSM fading correlation for $\phi_0 = 45^o$.

Figure 2.3 depicts the fading correlation envelopes for the CDSM DOA when $\phi_0 = 45°$. In Figure 2.3, increasing values of Δ denote larger scattering areas (as would be found in micro-cells with NLOS propagation). Thus, whereas $\Delta = 40°$ may be used to represent a NLOS micro-cell, a value of $\Delta = 10°$ may be used to represent a macro-cell. From the figure it is then clear that the CDSM indicates that larger antenna spacing is required in macro-cellular environments to decorrelate signals received by a diversity receiver. Conversely, this would mean that with fixed antenna spacing, larger diversity gains could be achieved in an environment where severe scattering is present than in an environment where few scattering points are present.

2.1.4 Angular Subscriber Distribution

In addition to dependence on the distribution of scattering elements, DOA distribution of signals in a cellular system is also dependent on the distribution of subscribers in a cell. In [126], Lötter showed that the manner in which subscribers are clustered together in angle (as would be the case on a road), significantly influences the gains that may be achieved by a space-time system. For instance, if the reference user and an interfering user are co-located in angle, no antenna pattern can be formed in either the up- or downlinks to reduce the interference experienced by the reference user. Therefore, the gain offered by, for instance, a transmit beamforming system to users in the relevant cell is negligible. On the other hand, having subscribers clustered in certain areas means that antenna sectors can be narrowed, thereby reducing interference to adjacent cells and increasing the overall network performance, even if the performance of all individual cells is not increased.

A number of approaches to the modeling of user locations have been followed in literature. For example, in [143] a uniformly distributed mobile user density is proposed, with a highway traffic distribution model presented in [144] and a modified Gaussian distribution proposed in [1]. The most accurate description of user locations would be gained from practical measurements at each site of interest. These assumptions are sufficient in the intended environments. A more general pdf that describes the user distribution, and is applicable to many scenarios, has been proposed in [126].

2.2 FADING DISTRIBUTION BASED ON SCATTERING ENVIRONMENT

According to Section 2.1.2, the choice of a channel model depends mainly on the operating environment of the communication system, with Rayleigh distributions commonly used for NLOS and Rician distributions commonly used for LOS propagation environments. An alternative to these fading distributions is the Nakagami or $m$distribution [132]. This distribution is defined as

$$p_S(s) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m s^{2m-1} e^{-ms^2/\Omega}, \tag{2.12}$$

where s denotes the received signal strength in volts, m is a parameter determining the fading characteristics of the signals and $\Omega = E(S^2)$.

One of the main advantages of the Nakagami distribution is its wide applicability. Specifically, the Nakagami distribution is equivalent to the Rayleigh distribution when $m = 1$, the onesided exponential distribution when $m = 0.5$, and it can also be used to model the Rician distributions with sufficient accuracy by setting [129, 130]

$$m = \left(1 - \left(\frac{\mathcal{K}}{1+\mathcal{K}}\right)\right)^{-1} \tag{2.13}$$

where $\mathcal{K}$ denotes the Rice parameter (average direct power/average scattered power). In addition to the attractive mathematical properties, it has also been shown in [133] that the Nakagami model can be used to accurately describe the fading behavior of multipath signals. Specifically it is shown that the Nakagami distribution can be used to describe varying physical scattering processes.

One of the important requirements in a spatial-temporal channel model is to incorporate the effect of the non-homogeneous geography of the cell into the temporal fading model used. Consider the case where, for instance, each multipath echo received at the base station is subject to Rayleigh fading. The question that arises is whether it is accurate to assume that all of the received multipath echos will have the same statistical fading distribution. Is it not possible that some of the received paths may contain a LOS component changing the distribution of the fading envelope from Rayleigh to Rician, or perhaps that some paths may exhibit more severe fading, i.e., as described by a one-sided exponential distribution? Examining results from extensive measurements, this is in fact the case. For example, in the experimental study in [145], the urban propagation channel is modeled as a Rician channel with varying $\mathcal{K}$ parameter. This indicates that an accurate model would describe the fading effects on each received multipath signal at the base station.

Following the approach of Lötter [126, 146], the fading process on each of the received multipath signals can be modeled by incorporating information on the DOA of the multipath signals at the base station. Utilizing the properties of the Nakagami distribution, varying degrees of fading can be approximated by the correct choice of the m parameter. In order to develop a relationship between the fading exhibited by a signal and its DOA, the results of [145] were used in [146].

2.3 SUMMARY OF SPACE-TIME CHANNEL MODELS

Thus far, all the elements required to accurately model the cellular channel have been presented. In Section 2.1, the concepts of fading, scattering environments, subscriber distribution and correlation were introduced. These aspects were further developed in this chapter where more comprehensive treatments of the CDSM and GS model were presented. In addition, the distribution of the fading envelope of multipath signals was explained in Section 2.2. In this section, all of the aspects of the channel model described in detail in the preceding section are combined and it is shown how a comprehensive channel model for use in the evaluation of cellular system models can be constructed.

Figure 2.4 depicts the process of constructing a channel model as a simple flow diagram. Let us first turn our attention to the choice of a cellular environment. This choice between the different cellular environments can firstly be viewed as a choice between a high-rank and a low-rank channel model. Environments with very low angular spread of the received signals are deemed to be low-rank channels and, in these cases, the description of the local scattering environment becomes less important. On the other hand, when the angular spread of the received signals is expected to be larger, the channel model can be described as high-rank, and consequently the description of the local scattering environment is of higher importance. Thus, in the case of a high rank channel model (which would be the predominant case in cellular environments), a decision must be made as to whether to describe the scattering area surrounding the base station or a mobile using the CDSM or the GS model. Both models will yield accurate results, with the GS model yielding a more general description.

The choice of the scatterer model will determine three additional channel model parameters, namely the correlation between the received signal envelopes at different points in space, the pdf of the received signal at the base station subsystem (BSS) and the characteristics of the temporal fading present on each multipath signal. The correlation between the received signal envelopes at different points in space will determine the possible gains that can be achieved using diversity systems. As the possible diversity gain is significantly influenced by the correlation between the fading envelopes, this part of the channel model is extremely important in order to accurately estimate the overall system performance. Whereas the correlation characteristics of the channel model influence mainly the diversity performance of the system, the pdf of the DOA at the BSS influences the performance of a beamforming system, as well as the fading characteristics of the received signals.

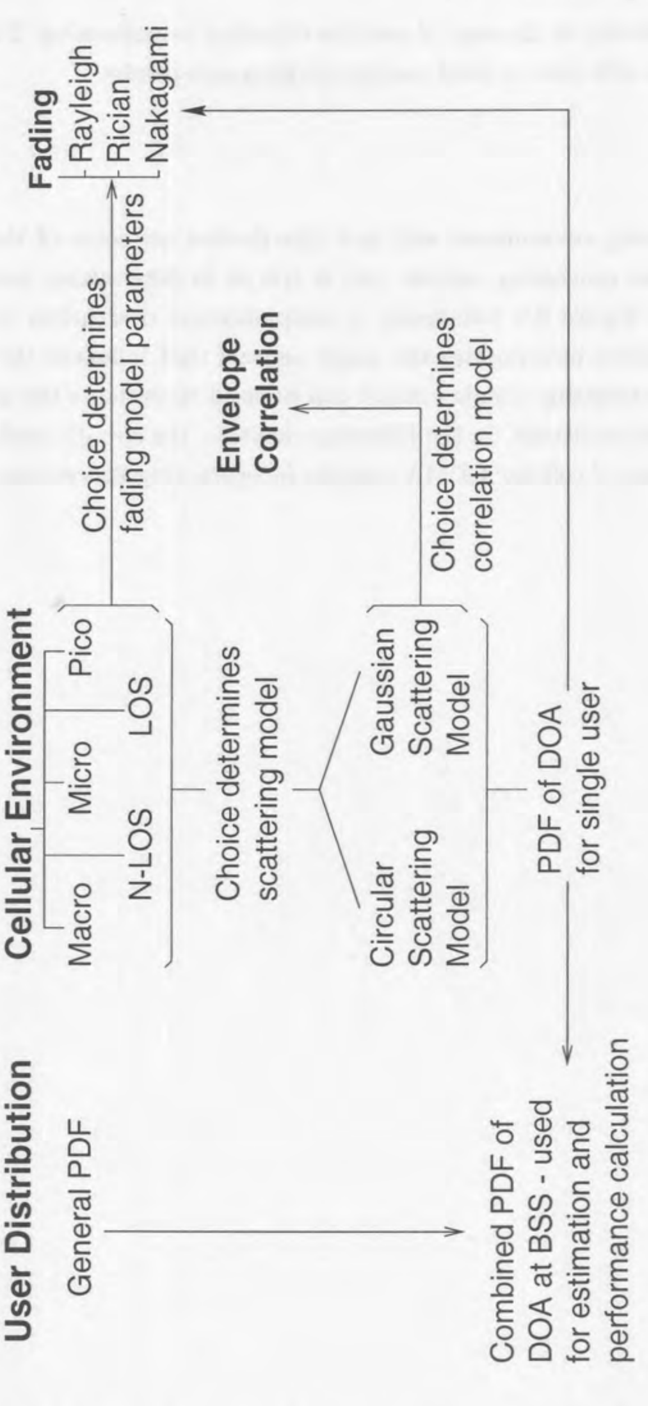

Figure 2.4. Constructing a typical cellular channel model.

Finally, the choice of cellular environment will determine the characteristics of the fading envelope of each received multipath signal. Generally, the received signal envelope is described as either Rayleigh, Rician or Nakagami. The Nakagami description provides the most general description of the fading characteristics and the use of this distribution is described in Section 2.2.

In addition to the choice of the environment, the choice of the user distribution will also significantly influence the performance of the cellular system. Thus, an estimation of the distribution of the user population based on the geographical environment where the users are active is required as one of the core ingredients of the channel model, specifically in the case of systems including beamforming. The general assumption of a uniform user distribution will tend to yield average performance results.

2.4 SUMMARY

Path loss, fading, scattering environment and user distribution are some of the key aspects limiting the performance of space-time processing systems and is crucial in determining mitigation techniques. With the process described in Figure 2.4 completed, a comprehensive description of the cellular environment is available. This description incorporates the major aspects that influence the performance of a cellular system and therefore the resulting channel model can be used to evaluate the performance of any cellular system under a variety of conditions. In the following chapters, the specific analysis techniques required to determine the performance of cellular CDMA systems incorporating space-time processing techniques will be presented.