CHAPTER 1

Introduction

Wireless communications technology has come a long way [1,2], dating back to the pioneering work by the Italian physicist Guglielmo Marconi (1874-1937) in the 1900s. He had demonstrated the feasibility of sending radio message signal over great distances which consequently led to the commercial realisation of the wireless telegraph stations network. It took another few decades or so before the cellular system concept was subsequently been introduced with several of its key technologies (including the seven-cell frequency-reuse technique) developed at AT&T Bell Laboratories during the 1960s [2]. This hence gave rise to the first generation (1G) analogue cellular system which was based on the Frequency Division Multiple Access (FDMA) technique. The cellular system was however made popular using the design based upon a high-capacity analogue standard developed by AT&T known as the Advanced Mobile Phone Service (AMPS). The standard was widely deployed in the United States and had gained widespread acceptance. Other popular standards [2] include the Nordic Mobile Telephone (NMT) and the Total Access Communications System (TACS) in Europe; the Nippon Telegraph and Telephone (NTT) and the Japanese

TACS (JTACS) in Japan; and the C-450 in Germany, bringing solely wireless voice access services to the Public Switched Telephone Network (PSTN).

In contrast to the first generation analogue systems, the second generation (2G) systems are designed for digital modulation transmissions. Unlike its analogue counterparts, the digital systems are able to provide flexible, secure, better quality, and higher capacity services. Advanced signal processing techniques can also be applied to the received digital signal to mitigate the effect of noise and multipath interferences encountered in the channel. The former FDMA scheme is however not implemented in the 2G systems. The scheme lacks the ability to utilise its resources efficiently as it requires the allocation of an entire frequency channel for the connection interval between the two users even though they do not converse 100% of the time in that whole duration. Digital systems which are capable of handling discontinuous transmission/reception thus pave the way for better multiple-access candidates, such as the Time Division Multiple Access (TDMA) and the Code Division Multiple Access (CDMA) schemes, to be employed in the system [2]. By far, the most successful 2G system is the Global System for Mobile communications (GSM), which is the first digital standard developed to establish cellular compatibility throughout Europe. Its success has spread to many countries, creating a mass market for mobile communications and a high terminal penetration in the global markets. Similar standards that are based upon TDMA include the North America IS-54 system which is basically a digital variation of AMPS (also known as D-AMPS), the Japanese Personal Digital Cellular (PDC) system, and etc [3]. IS-95 on the other hand is based on CDMA, which consequently forms the basis for the third generation (3G) cellular system.

Just when the second generation systems were widely being deployed, works were already underway to develop the third generation (3G) system. The projected growth in the demand for capacities, data rates and services, calls for the need to have a new network standard. The International Telecommunication Union (ITU) hence formulated an initiative called the Future Public Land Mobile Telephone Systems (FPLMTS), which was later renamed as the International Mobile

Telecommunications 2000 (IMT-2000) in 1995. The IMT-2000 is the 3G cellular standard [4] aimed at providing ubiquitous wireless access to the global telecommunication infrastructure through both satellite and terrestrial systems. Its main goals encompass a maximum data rate of 2Mbits/s, a higher capacity, and an ability to support multimedia voice/video/data services [5]. CDMA scheme, as seen employed in the second generation system, is envisaged to play an important role in its air interface protocol. In fact, the European Telecommunications Standards Institute (ETSI) has developed the Universal Mobile Telecommunications System (UMTS) based on Wideband Code Division Multiple Access (WCDMA), which is one of the major 3G mobile communications systems within the IMT-2000 framework. However to sustain the IMT-2000 vision in the long run, new enabling technology has to be included to enhance the capability of the system [6]. The use of antenna arrays, which is regarded as a core component in the future-generation mobile networks, thus becomes a viable option to be embedded in the system [6-8]. In fact, the current UMTS standard has already provided for the use of sensor array [9] and there is presently a major thrust to make space-time processing an important part of the 3G networks. Subsequent sections will hence give further insights into these two key technologies: CDMA and space-time array processing, which when combined together will play a significant role in the future of the next-generation wireless communications system.

1.1 Spread Spectrum Multiple Access Scheme

Multiple access scheme is an allocation strategy in apportioning the available physical communication resources among several simultaneous transmitters sharing a single common channel. To avoid co-channel interference (CCI), the physical resources readily accessible to allocation can be categorised in terms of its space, time or frequency domain as illustrated in Figure 1.1. As seen from the figure, Frequency Division Multiple Access - FDMA (see Figure 1.1a) ensures its resulting spectra will not overlap with one another by allocating different carrier frequency to each of the users sharing the same space and time domains;

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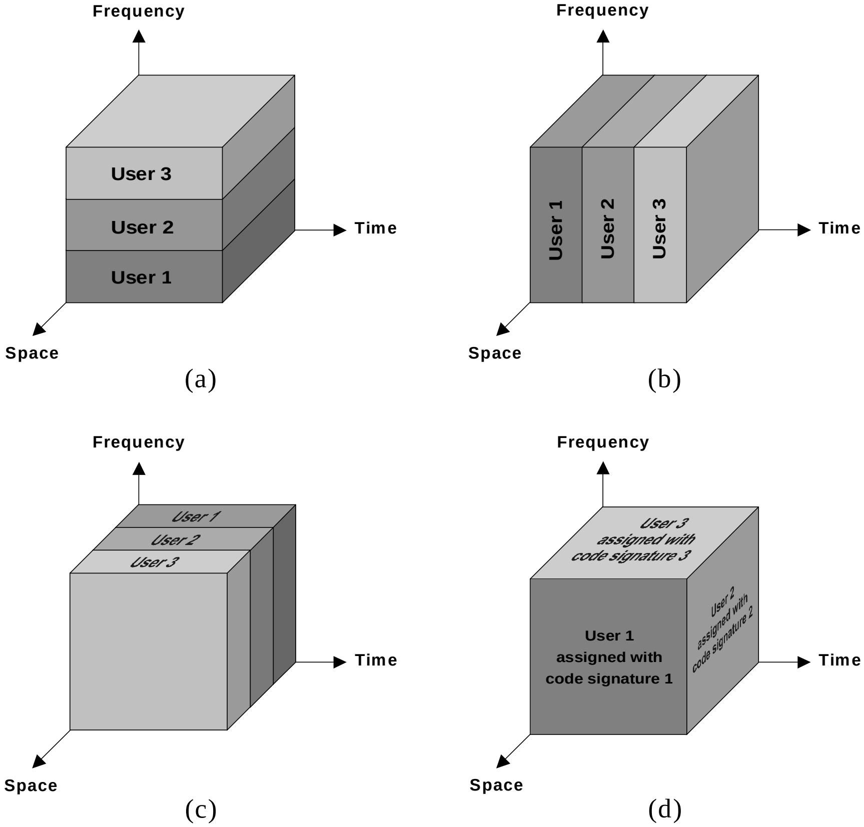

Figure 1.1: Multiple access schemes: (a) Frequency Division Multiple Access (FDMA), (b) Time Division Multiple Access (TDMA), (c) Space Division Multiple Access (SDMA), and (d) Code Division Multiple Access (CDMA).

Time Division Multiple Access - TDMA (see Figure 1.1b) on the other hand makes the channel orthogonal in the temporal domain by assigning different time slot to every of its users; and Spatial Division Multiple Access - SDMA (see Figure 1.1c) provides virtual spatial channel among the users by controlling its space domain using antenna arrays [10-12]. However, an alternative allocation strategy can be established without having to perform segregations in the space, time or frequency domain: Code Division Multiple Access - CDMA (see Figure 1.1d) allows the simultaneous usage of all the three overlapping physical resources by introducing a unique identification code assigned to each user. Unlike the above physical resources, such purposeful introduction opens up an extra domain of separation to differentiate every of its individual users.

CDMA [13] is a multiple access spread spectrum scheme originated from past military applications. The primary objectives of the scheme encompass hiding its transmitted signal from unwanted eavesdroppers (i.e. low probability of detection), encrypting its data information from unintended interceptors (i.e. low probability of interception), and immunising its communication link against deliberate jammers' interferences (i.e. anti-jamming). It involves spreading the information signal over a much greater spectrum bandwidth so that it appears virtually indistinguishable from the inherent background noise. The technological concept was then borrowed and commercialised by Qualcomm Inc. for the burgeoning cellular telecommunication industry. Since then, several variants of the CDMA schemes have been devised. The three commonly-used schemes [14] are DS-CDMA (Direct Sequence), FH-CDMA (Frequency Hopping), and TH-CDMA (Time Hopping). And the hybrids of these three schemes include DS/TH, DS/FH, FH/TH, and others [15-18]. However among these, the DS-CDMA scheme is the most widely deployed in commercial spread spectrum mobile system. In fact, the scheme, which is the focus of this book, has already been employed in the 2G IS-95 cellular network and chosen as the air-interface for the 3G UMTS standard [19].

To satisfy the requirements of the 3G mobile systems, the spread spectrum scheme possesses characteristics that have distinct advantages over other multiple access techniques. Chief among these is the universal frequency-reuse attribute that allows the users to share the same frequency band in a cellular network. Not only does this helps in increasing the efficiency of the spectrum usage, but also saves the hassle of frequency planning for the neighbouring cells or users. Besides that, it permits soft handover across multiple cell base stations by allowing connection to the new cell to be made before connection to the current cell is broken. This thus avoids the disruptive abrupt transitions encountered in conventional hard handover, consequently aids in reducing its associated dropped-call probability and improving its corresponding cell-boundary performance. Another major benefit of the scheme is the dynamic sharing of channel resources. The scheme can accommodate a higher system capacity which is dependent on the number of simultaneous active users in the cell. Unlike other multiple access schemes, its system capacity can be increased with trade-off against the quality of service (QoS). Such dynamic sharing property provides operational flexibility in its provision of services. A wide range of multimedia services with different quality requirements - such as voice, video or data service, as well as a combination of these services - can thus be supported concurrently in the system. Lastly the scheme, originated previously from military purposes, inherits the advantage of improved security and privacy. Its working function also allows coexistence operation with other narrowband microwave system.

However the spread spectrum scheme entails some disadvantages. As with other multiple access techniques involving orthogonal space, time or frequency allocation, the scheme maintains its orthogonality by means of a set of spread spectrum code signatures in a synchronous environment. But in an asynchronous setup with uncoordinated transmissions from the multiplicity of users, its non-alignment in time epochs will create quasi-orthogonality among the users, thus resulting in Multiple-Access Interference (MAI). Such level of MAI will increase with the number of users and, if left uncontrolled, may have an adverse effect on the system performance. Another drawback in the scheme is the near-far effect. If all the users in the spread spectrum scheme are transmitting at the same power level, the received signal from users who are closer to the receiver will be stronger than those who are farther away. This will inevitably lead to performance inconsistency depending on the users' location in the cell. But what is critical is that every of these nearby users, who are essentially more powerful at the receiver, will each cause some interferences to those distant users, hence creating a much higher MAI effect. This phenomenon is known as the near-far problem [14]. Power control is hence introduced in order to curb the transmitted power of those who are closer and heighten that of those who are farther to alleviate this effect. Nonetheless in practice, such power control, be it open loop or closed loop, requires knowledge of the propagation channel between the transmitter and receiver. This will consequently impose additional complexity in the system. Alternatively, appropriate design of the receiver, taking into account the above two drawbacks, can robustify the system against these shortcomings. Such robustification design in the receiver will be delineated in this study.

1.2 Antenna Array Communications

Antenna array processing for wireless communications is an evolution from the more traditional array signal processing technique. Typical technique centred primarily around conventional beamforming-based methods from a spatial perspective [20], such as the classical Bartlett beamformer [21] and Capon's Minimum Variance Distortionless Response (MVDR) beamformer [22]. Most of these techniques, however, have some fundamental limitations in their spectral resolution. The high resolution subspace-based approach, due to the introduction of the well-known MUltiple SIgnal Classification (MUSIC) algorithm [23], hence draws tremendous interest. Since then, several variants of the algorithm have been devised, such as Root-MUSIC [24], Cyclic-MUSIC [25], Beamspace-MUSIC [26], etc. Other notable subspace-based algorithms include the Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) introduced by Roy and Kailath [27], the Minimum-Norm (Min-Norm) algorithm suggested by Kumaresan and Tufts [28], and the Weighted Subspace Fitting (WSF) method proposed by Viberg and Ottersten [29]. Another commonly-used optimal array processing model is the maximum likelihood [30] approach, encompassing Stochastic or Unconditional Maximum Likelihood (SML or UML) technique [31,32] and Deterministic or Conditional Maximum Likelihood (DML or CML) technique [33-35].

Array communications, in essence, are based from these traditional processing techniques but are extended to exploit the rich structure of the propagating signals and incorporate them within the wireless communications process. However the realisable processing gain is largely dependent on the several parameters associated with the wireless multipath propagation channel. Hence an understanding of the various channel aspects influencing the space-time processing performance of the communications system is therefore necessary.

1.2.1 Wireless Multipath Channel Characterisation

In the study of wireless communications system, the classical additive white Gaussian noise (AWGN) channel is normally the starting point in understanding the basic performance relationships. The primary source of performance degradation for such an ideal channel is solely the noise inherent in the system. However, external interferences as a result of channel propagation often have a much more significant deteriorating effect on the system performance. In practical scenarios, the transmitted signal propagating through the channel interacts with the environment in a rather complex manner. The four underlying interacting mechanisms in the environment can be categorised as follows: reflection of signal from sizeable obstruction, refraction of signal through penetrable obstruction, diffraction of signal around narrow-edged obstruction, and scattering of signal from rough-surfaced obstruction. Such complex interaction causes

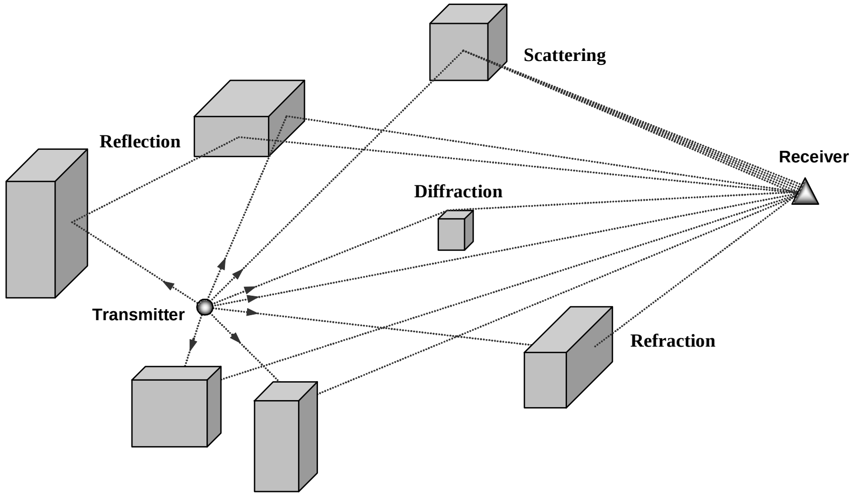

Figure 1.2: Multipath propagation environment.

multiple replicas of the signal arriving along a number of different paths at the receiver, referred to as multipath propagation. A simplified illustration of the multipath environment is as depicted in Figure 1.2.

In addition to that, the received signal also suffers a weaker power level than its original transmitted signal due to the effects of path loss and fading existing in the propagation channel. The mean path loss describes the attenuation of the signal in a free-space propagation environment, which is defined as an ideal obstruction-free transmission medium. In such free-space environment, the signal's attenuation is modelled as a function of its propagation distance and it behaves according to an inverse square law (that is, with an attenuation power exponent of 2). But in a real practical environment with the presence of obstructions, the attenuation power exponent may vary with typical values in the order of between 2 to 5 [36]. Fading, on the other hand, refers to the fluctuation in the received signal level experienced in the channel. The causes of fading can be attributed and broadly classified into two main classes: slow fading and fast fading. Slow fading, or long-term fading, is as a result of the blocking effect, also known as the shadowing effect, caused by prominent terrain contours such as hills, forests, buildings etc. Such random shadowing effect encountered by the signal along its propagation path describes a log-normal distribution about its distance-dependent mean path loss. This phenomenon is often termed as log-normal shadowing. Fast fading, or short-term fading, in contrast is due to the different multipath signals being added up with random phases, constructively or destructively, at the receiver. This hence gives rise to the rapid and dramatic fluctuations in the received signal level with its local average signal level following that of the long-term fading model. If the number of multipath is large and there is non line-of-sight (NLOS) signal component, the fast fading envelope of the received signal can be statistically approximated by a Rayleigh density function. Whereas in the presence of a direct line-of-sight (LOS) signal path, this envelope becomes no longer Rayleigh distributed and it is well described by a Ricean density function. But for some environments, experimental measurements have shown to support a better model of the fading envelope which is that of a Nakagami distribution [37].

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Besides the above detrimental effects, multipath propagation also creates dispersion in the channel across a number of domains. Such channel dispersion is as a result of the received signal energy being spread in any of the frequency, time, space or polarisation dimension. The characteristics of these four different spreads - known as the Doppler spread, delay spread, angular spread and polarisation spread respectively - are briefly described as follows.

> ***Doppler spread*** describes the time-varying nature of the channel that is caused by either the relative motion between the transmitter and the receiver or by the movement of the obstructions in the channel. It is a measure of the spectral broadening width defined as the range of Doppler shift frequencies over which the received Doppler power spectrum is essentially non-zero [38]. By considering its Fourier transform pair, the reciprocal of this spectral broadening width is effectively the coherence time of the channel. Coherence time is therefore the time domain dual of Doppler spread and it represents the time duration over which the channel impulse response is essentially time-invariant. Hence a fast varying channel will tend to have a smaller coherence time, or equivalently, a larger Doppler spread. If the reciprocal bandwidth of the baseband message signal is greater than the coherence time of the channel, its channel characteristic will consequently be changed in the duration of the message signal, thus giving rise to the so-called time-selective fading situation.
>
> ***Delay spread*** is as a result of multipath arriving at the receiver with different time delay, and is defined as the propagation time difference between its longest and shortest received signal path. Similarly, its analogous Fourier transformation relationship characterises the inverse of the delay spread as a measure of the coherence

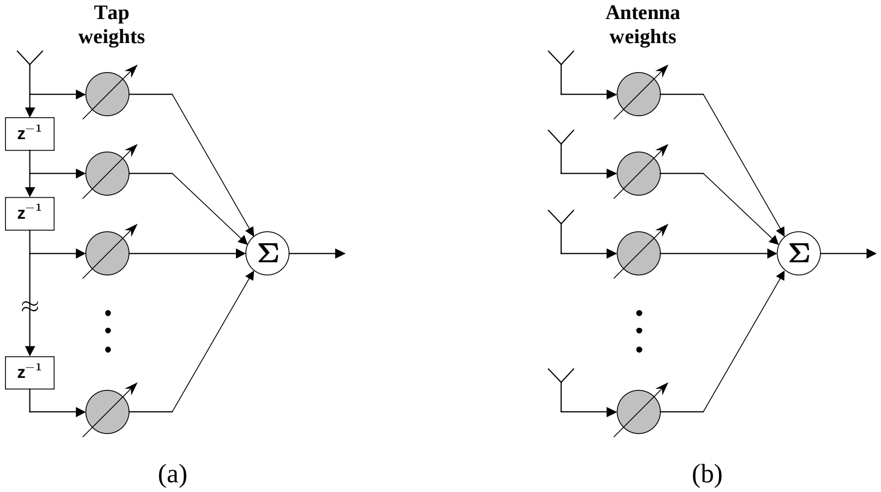
bandwidth of the channel. This time, the channel coherence bandwidth is the duality of the delay spread in the frequency domain. It is a statistical measure of the range of frequencies over which the channel passes all its spectral components with almost equal gain and linear phase. In other words, the coherence bandwidth specifies the maximum range of frequencies over which its channel response will remain relatively constant. Thus, a signal is said to experience flat fading (or frequency-flat fading) if its bandwidth is below the coherence bandwidth of the channel. In contrast, if the bandwidth of the message signal exceeds the coherence bandwidth, the time-dispersive channel is termed to exhibit frequency-selective fading. Besides that, this condition also induces another form of fading degradation which is caused by the Inter-Symbol Interference (ISI) contributions from its received multipath components.

Angular spread arises from the different arriving angles of the incoming multipath impinging on the antenna array. The amount of the spread is dependent on the signal propagation environment, which is high in an urban case and low in a rural scenario. In a similar manner, its associated coherence distance is inversely related to the angular spread, and is defined as the range of space for which their channel responses are strongly correlated. In other words, coherence distance represents the maximum spatial separation between the antenna elements whereby their fading effects are relatively the same. Thus if the angular spread is considerably large, all the incoming multipath components will be added up randomly at each of the antenna element, bringing about space-selective fading. Hence antenna array elements that are spaced above the coherence distance tend to experience uncorrelated fading which is a prerequisite for the application of space diversity [39,40].

> ***Polarisation spread*** refers to the diverseness in the polarisation of the multipath electromagnetic waves incident onto the receiving antenna element. The polarisation of the received multipath component is oftentimes not what is originally intended at the antenna end of the transmitting device. This is due to the change in the polarisation state of the electromagnetic wave, brought about by the complex interaction of the wave, in the form of reflection, refraction, diffraction and scattering, within the propagation channel. Such alteration in polarisation through multipath propagation is known as depolarisation [41]. In addition to that, the random orientation of the portable transmitting device also plays a significant part in varying its intended transmitted polarisation from one state to another. This diverseness in the received polarisation state is consequently the cause of polarisation fading [42], whereby the signal fades up and down depending on the relative alignment of its electric field with respect to the receiving antenna element. Not only that, it is also the decorrelation mechanism behind the source of polarisation diversity [43,44] in order to achieve low correlation [45] between its diversity branches.

1.2.2 Space-Time Array Processing

The above degradation effects introduced by the propagation channel cause the transmitted signal to be distorted at the received end of the communication link. The general approach to improve the system performance is to employ some form of mitigation to remove or reduce the amount of such signal distortion. This is incisively the motivation underlying space-time array processing, which exploits the spatial and temporal dimensions of the received signal to overcome the various channel impairments. The technique, in principle, combines the benefits of both the time-only and the space-only processing configurations to enhance the performance of the communication link.



(a) (b)

Figure 1.3: Analogy between (a) time-only processing equaliser, and (b) space-only processing beamformer.

Time-only processing generally corresponds to the temporal equalisation of the received signal as illustrated in Figure 1.3a. The equaliser forms a weighted sum of its discrete-time sample outputs corresponding to a single receiving antenna element. The principal behind the equalisation is an attempt to yield a net overall channel response effect that is flat with phase linearity. Time-only processing technique hence offers a very efficient mitigation against channel-induced ISI arising from frequency-selective fading effect. This process of equalising the ISI is in effect gathering the dispersed symbol energy back into its original time intervals so that it will not be lost and be an interference to other symbols. Space-only processing, on the other hand, can be viewed analogously as being the equalisation of the received signal in the spatial domain as shown in Figure 1.3b. The equaliser is realised by implementing more than one antenna element to create a beamformer that takes a weighted sum of its received antenna outputs. The operation of the beamformer basically steers its mainlobe beam towards the direction of a particular user of interest whilst nulling the contributions from the rest of its co-channel users. This therefore makes space-only processing technique an efficient mitigation in suppressing the effects of CCI/MAI in the channel.

In contrast, space-time processing embodies both the ISI and CCI/MAI mitigation superiorities by putting together the two temporal and spatial signal processing techniques. This new spatial-temporal dimension allows interference cancellation to be performed in a way that is not possible with solely the time-only or space-only processing technique. Its classification [46] can be generally categorised into two broad families: decoupled space-time processing and joint space-time processing. The former typically involves a spatial beamformer at the front-end of its configuration followed by a temporal processor. The main idea of decoupled space-time processing [47-52] is to separate CCI/MAI and ISI mitigation into two processing stages. The beamsteering processor first aids in the suppression of the CCI/MAI contributions while preserving all the ISI structure of the desired signal to be exploited later by the temporal equaliser. The latter joint space-time processing [51-58] however exploits the conjoined spatial and temporal signatures of the multipath as a means of signal differentiation. This provides more degrees of freedom than its decoupled counterpart in the suppression of both the ISI and CCI/MAI effects in the channel. As such, its combat against interference is no longer dependent on the individual consideration of the space followed by time differentiation, but on the joint spatial-temporal distinction attributed to each multipath.

In addition to that, space-time processing permits the spatial and temporal consideration of the multipath propagation channel to be incorporated as an inherent source of diversity in the receiver architecture. Diversity is a powerful technique employed extensively in wireless communications network to alleviate the effects of channel fading. Traditionally, this source of diversity can be achieved by transmitting multiple copies of the signal in any of the frequency, time, space or polarisation domains. In other words, replicas of the same information signal can be rendered and transmitted by means of different carrier frequencies, different time slots, different positional spaces, or different states of polarisation. The basic idea of such diversity concept is to create several copies of the same information carrying signal so that each of them will tend to fade independently in the channel; and hence will be less likely for them to suffer simultaneous deep fade at the receiver for any given instant of time. However instead of having the transmitter deliberately generating these multiple copies of the signal, the receiver can employ spatial-temporal processing technique to exploit and derive the source of diversity that is already inherent in the multipath environment. Hence, in summary, space-time processing is capable of not only providing a mitigation of the prejudicial multipath channel effects, but also offering a source of diversity from the multiple signal replicas formed in the propagation channel.

The implementation of space-time processing in wireless communications can provide several significant leverages to enhance the performance of the cellular network system. First of all is the network capacity. As a result of its capability of suppressing the effects of CCI/MAI and ISI in the channel, the number of active users that can be supported in each cell for a given quality of service can thus be significantly increased. This hence gives rise to a gain in its system capacity and brings about an improvement in its spectrum efficiency. Second is the link quality. The quality of the link can be ameliorated by means of combining the diverse multipath contributions inherently present in the otherwise detrimental propagation environment. Finally the third is the range coverage. The high directivity and gain associated with space-time array system allows its corresponding reception range to be extended, hence leading to a larger and better cell coverage. This also entails that lesser transmit power is now required for a given reception distance, consequently resulting in an increase in its transmission efficiency. Besides that, multiple beams can also be employed to dynamically track the transmitters so as to reduce the level of hand-off rate in the cellular network.

1.3 Motivation and Organisation of Book

From the discussions in Sections 1.1 and 1.2, it is therefore conceivable that the integration of space-time array processing and spread spectrum multiple access scheme will bring about a synergetic impact on the overall performance of the wireless communications system. The introduction of the multiple antenna elements, facilitating the application of space-time processing, adds a new dimension in the conception of the spread spectrum estimation/reception process. With the aid of space-time processing, coupled with the exploitation of the DS-CDMA data structure, (1) extra layer of interference cancellation can now be devised, as well as (2) the alleviation of the multipath channel fading effects being instead incorporated as a source of diversity in the receiver design. However the implementation and performance improvements of space-time processing in DS-CDMA scheme are, to a large extent, related to the channel scenario under consideration and the form of diversity that can be derived from the system. Specifically developed space-time vector channel estimation and reception algorithms are thus proposed based on these different environmental context. This hence forms the subject of this written text, which is structured in the outline as follows.

Chapter 2 will first provide an overview of the spatial-temporal array architectural system which is founded on fusing space-time array processing with spread spectrum multiple access scheme. The system model covers from the transmission of the signal, propagation through the multiuser space-time channel, down to its reception at the array front-end. This modelling forms the basic mathematical framework for later formulation in the subsequent chapters.

Chapter 3 introduces the notion of exploiting the polarisation domain of the signal inherent in the environment as a form of diversity and as a means of signal discrimination. This can be achieved by utilising polarisation-sensitive sensor array to capture all the incoming diversely-polarised multipath signals impinging on the sensor elements. More often than not, this diverse polarisation information available in the propagation channel is oftentimes being ignored at the receiver's estimation and reception process. The polarisation of the signal is either assumed to be perfectly aligned with the orientation of the receiving sensor elements, or regarded to be part of the signal fading effect. On the contrary, this work will look at how this polarisation information can be incorporated in the space-time processing of the signal, and the different ways in which the performance of the resulted system can be improved.

Chapter 4 addresses the issue of signal diffusion as a result of the scattering mechanism intrinsical in the propagation environment. The diffuse signal is basically a conglomeration of multiple point sources superimposed together to create the spreading phenomenon as seen in the signal cluster. This hence results in performance degradation if conventional space-time processing techniques based on point sources assumption are applied. In this study, a generalised diffusion framework is attempted in the receiver design in order to handle the occurrences of both point and/or diffuse sources. The algorithm is robust against any incorrect or incomplete erroneous estimates incurring in the estimation process. And due to its underlying structure, the final outcome of the system is also capable of operating in either a co-code (brought about as a consequence of intentional code-reuse scenario or unintentional jamming situation) or a non co-code user environment.

Chapter 5 investigates the derivation of Doppler diversity in an asynchronous Multiple Input and Multiple Output (MIMO) system. Essentially, the Doppler spreading effect, which is normally treated as an impairment factor, constitutes a multiplicity of the signal components dispersed in the frequency domain. By employing the spatial-temporal array architecture at the front-end of the MIMO receiver, instead of the traditional multiple independent-antenna configuration, such channel dispersion can be taken into consideration in the devised space-time processing operation. Additional form of diversity in the Doppler frequency domain can also be derived and be incorporated in the system design. Not only that, the blind near-far resistant MIMO receiver, unlike its conventional MIMO counterparts, does not require the imposition in the need of any power control or any knowledge of the channel.

Chapter 6 looks at some other research works applying the above algorithmic framework in accordance to the context of its environment. These representative examples are included to help in gaining a better understanding and new perspective in the devised space-time vector channel estimation and reception algorithms.

Chapter 7 finally gives an overall concluding view of the current study, and thenceforth identifies potential areas for future research work.