

Recent Advances in Propagation Characterisation and Multiple Antenna Processing in the 3GPP Framework

Laurent Schumacher, Lars Torsten Berger and Juan Ramiro-Moreno

Center for PersonKommunikation, Aalborg University
Niels Jernes Vej 12
DK-9220 Aalborg East, Denmark
E-mail: {ls, ltb, jrm} @cpk.auc.dk

Abstract— This document gives an overview of recent achievements of various research teams, both academic and industrial, in the characterisation and the exploitation of the essential properties of multiple antenna systems. It is organised into two main parts. The first part looks at recent modelling activities of Multiple-Input Multiple-Output (MIMO) radio channels, while the second tackles advanced antenna processing suggested in the Multiple-Input Single-Output (MISO) and MIMO perspectives. In the second part, a strong emphasis is given to the standardisation of the evolution of the Third Generation (3G) cellular systems within the Third Generation Partnership Project (3GPP).

I. INTRODUCTION

Having explored time-, frequency- and code-domain to improve the quality of wireless, multiple access communication links, the exploitation of the space domain has appeared for the last years as the quest to the final frontier. Initiated as a mean to improve the performance of existing systems through spatial filtering of interference, this search reached a major milestone when it was made clear that the deployment of multiple antenna elements at both ends of the link promises significant capacity increase. The fundamental paper of Telatar [1] has since opened the road to research activities in both the academic and the industrial world.

However, on the road towards the high capacity figures promised by MIMO systems, the first step leads to an appropriate characterisation of the wave propagation between the connection terminations. Significant work had been performed for Single-Input Multiple-Output (SIMO) systems [2], [3]. Based on that work, the characterisation of the space domain has progressed further, to encompass MIMO systems. Section II will present an overview of the work performed in that direction, and of its impact on Third Generation (3G) cellular networks standardisation.

The Third Generation Partnership Project (3GPP) identified MIMO systems as a mean to improve coverage and link reliability, and to significantly increase the overall capacity of Universal Mobile Telecommunications System (UMTS) networks [4]. Section III will group multiple antenna element schemes as proposed for the UMTS Frequency Division Duplex (FDD) downlink into four main categories and will point out some practical considerations influencing system performance.

II. PROPAGATION CHARACTERISATION

Although the characterisation of wireless channels started some decades ago, and has since been the subject of intense research activities, it still attracts lots of interest. One of the main reasons for this continuing interest is the fact that, until some years ago, most of the modelling activities have focused on the time-domain aspects. This has led to a large set of models, which can be sorted according to the outdoor vs. indoor dichotomy. Usually, in outdoor scenarios, the fixed Node B¹ is located much higher than the mobile User Equipment (UE²), such that the scatterers which account for the diffuse transmission of the signals are mostly lying close to the UE. On the contrary, in indoor scenarios, the environment surrounding UE and Node B is much more similar. It does introduce symmetry to the propagation phenomena. This dichotomy led to the development of two sets of models, the first one accounting for outdoor, mobile scenarios, while the second one describes indoor, portable ones. The models proposed by [5], [6] are among the most widely accepted for the outdoor environments. They account for the time dispersion and the time variation of the mobile channel. On the other hand, the model proposed in [7] focuses on indoor phenomena.

These time-domain models have been applied successfully until quite recently, when the growing demand for ubiquitous high speed connections pushed researchers to investigate new means to increase the capacity of wireless channels. As part of these efforts, the use of so-called "smart antennas" for antenna/space diversity, beamforming or even Space Division Multiple Access, has been regarded as a powerful improvement [2]. However, the classical non-directional radio channel models were not of immediate help, as they do not appropriately model the propagation phenomena in the space domain. Many authors have proposed models solving this lack. Some suggested an upgraded version of pure time-domain models, such as [21] for outdoor and [22] for indoor environments. Others proposed new models, based either on a geometric description of the scattering process used to compute Power Delay Spectrum (PDS) and Power Azimuth Spectrum (PAS) according to propagation laws,

¹UMTS terminology for Base Station.

²UMTS terminology for Mobile Station.

Polarisation	Reference	Set-up	Spacing [λ]		Carrier [GHz]	Bandwidth [MHz]	Time resolution [ns]	Environment
			Tx	Rx				
Single	[8]	$n \times 8^3$	-	-	1.7	30	-	Outdoor micro- and macro-cells
	[9]	8×8	n.a.	0.5	5.2	120	15	LOS/NLOS indoor micro-cells
	[10]	$n \times 8^4$	-	0.5	5.2	120	15	LOS/NLOS outdoor
	[11]	3×21^3	6	0.25	5.8	400	-	NLOS indoor
	[12]	8×8	0.5	0.5	5.2	120	-	LOS/NLOS indoor
	[13]	4×12	6	-	2	5	-	Outdoor urban
	[14]	4×12	1	-	2	5	-	Outdoor urban
	[15, p. 24]	4×4	3-7	1-3	0.9	35	11	Subway
	[15, p. 17]	17×9^6	0.25	0.25	5.2	250 62.5	4 4	Indoor Outdoor
Dual	[16] ⁷	4×4	0.4	1.5	2.05	5	122	Outdoor-to-indoor micro-cells, indoor pico-cells
	[17]	4×4	0.5	20	1.9	0.03	-	Outdoor-to-outdoor and outdoor-to-indoor suburban
	[18]	12×15	0.5	0.5	1.95	0.03	-	Indoor
	[19]	16×64	0.718	-	2.154	-	33	Outdoor-to-indoor
	[20]	4×4	40	1	-	3.5	-	Urban/suburban, hilly areas
	[15, p. 27]	4×8	-	-	2	120	-	Urban outdoor

TABLE I
DESCRIPTION OF MIMO MEASUREMENT CAMPAIGNS

or based on empirical models fitting measurement results. [2], [3] present comprehensive surveys of these efforts.

However, these surveys focus on SIMO systems, where multiple antenna elements are only deployed at one connection termination. The point here is to address Multiple-Input Multiple-Output (MIMO) channels. The following paragraphs distinguish between deterministic and stochastic models. Within the deterministic category, another distinction will be made between the reproduction of recorded impulse responses and ray-tracing strategies. In the stochastic section, three sub-categories will be introduced, namely geometrically-based, parametric and correlation-based models. Figure 1 gives an overview of these categories.

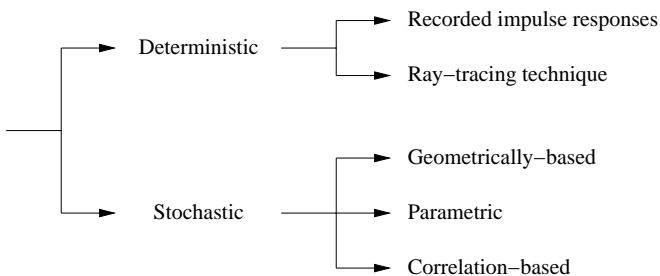


Fig. 1. Categories of MIMO channel models

In the following \mathbf{H} will represent the $n_{Rx} \times n_{Tx}$ narrowband transfer matrix of a MIMO system whose transmitter and re-

ceiver deploy respectively n_{Tx} and n_{Rx} antenna elements. The elements of \mathbf{H} write $h_{i,j}$ with $i \in [1..n_{Rx}]$ and $j \in [1..n_{Tx}]$.

A. Deterministic models

Deterministic models are based on an accurate description of a specific propagation environment. Two deterministic approaches towards the characterisation of MIMO channels are described in the next paragraphs, namely the collection of impulse responses and the ray-tracing technique.

A.1 Exploitation of recorded impulse responses

Propagation studies often rely on measurement campaigns. Their results enable to extract the typical parameters characterising a given environment. Table I summarises the most significant characteristics of the experimental set-ups designed so far to investigate MIMO channels. This table encompasses actual and synthesised measurement campaigns. In the former case, both transmitter and receiver actually deploy multiple antenna elements. In the latter case, virtual MIMO systems are studied after post-processing of SIMO measurements, where the single antenna has been moved along a given surface according to a regular pattern, see for instance [10] and [15, p. 17].

³Directional array antenna at the transmitter.

⁴Single moving antenna at the transmitter.

⁵Single moving antennas at both connection terminations. SISO measurements post-processed to generate MIMO channels.

⁶Single moving omni-directional antenna at transmitter.

⁷Second set-up.

Despite the numerous measurement campaigns performed, it is very rare that the recorded impulse responses are used as such to simulate radio channels. Obviously, this methodology suffers from the significant memory resources it requires and the fact that the channel responses are rather site-specific. Note however that such propagation databases exist [23].

A.2 Ray-tracing technique

Based on geometric optics, the ray-tracing technique predicts the multipath propagation in a given environment, from its geometrical description (architecture drawings, building databases) and its electro-magnetic properties. It enables to estimate not only the signals' strength but also their Directions-of-Departure (DoD) and Directions-of-Arrival (DoA). Unfortunately, ray-tracing is also the most computationally demanding and the least flexible, because its results are intrinsically tied to the environment in which they have been derived. Two examples of ray-tracing applied to MIMO are given in [24] and [25].

B. Stochastic models

Contrary to deterministic models, stochastic models do not rely on a site-specific description. They rather aim at reproducing observed phenomena by statistical means. Therefore, they reflect the propagation environment in an indirect way. Stochastic models often serve to assess the performance of algorithms like the ones listed in Section III.

The most comprehensive attempt to statistically model directional channels so far is most likely the COST 259 Directional Channel Model (COST 259-DCM) [26, Section 3.2]. It has a three-level top-bottom structure consisting of the cell type (macro-, micro- or pico-cell), the Radio Environment (RE) and the Local Parameters (LPs) of the detailed propagation scenario. A given set (cell type/RE/LP) fully characterises a simulation environment. Therefore, the COST259-DCM is not just an implementation, but rather a model framework enabling to tune the parameters of a specific implementation.

The following paragraphs will detail three possible implementations of stochastic MIMO models, namely geometrically-based, parametric and correlation-based models. These implementations are however interrelated. The connection between the first two kinds is analytically demonstrated by the equations shown in [26, p. 158] and experimentally illustrated in [10]. On the other hand, the mapping between a geometrically-based model and a correlation-based one is described in [27], [28].

B.1 Geometrically-based stochastic models

Geometrically-Based Stochastic Models (GBSM) assume a stochastic distribution of scatterers around the two ends of the connection. The channel model is derived from the positions of the scatterers, by applying the fundamental laws of specular reflection, diffraction and scattering of electro-magnetic waves.

The shape of the scattering area often accounts for a given kind of scenario. Usually, macro-cells are simulated by distributing scatterers around the UE, while micro-cells involve ellipses whose foci are the Node B and the UE location. On the other hand, the scatterer density within a scattering area, and

also their gathering into clusters, are user-defined parameters that help to achieve a more trustworthy simulation of the propagation scenario. Having scatterers uniformly distributed on a circle centered on the UE generates the well-known Clarke's Doppler spectrum. Numerous measurements have shown however that wavefronts could impinge the receiver under a limited set of DoAs, with a certain Angular Spread (AS). Such configurations are emulated with clusters lying in the DoAs, which sizes match the observed ASs.

A classic GBSM, called Wideband Directional Channel Model (WDCM), is presented in [8], [29]. It is parametrised for micro- and macro-cells, using the corresponding circular and elliptical distribution area of scatterers. The size of these shapes is derived from the dimensions of the propagation environment. The scatterers are grouped in clusters uniformly distributed in space, in which the location of the scatterers follows a Gaussian distribution around the central point. However, the WDCM only accounts for a single specular reflection. Neither scattering, diffraction nor multiple bounces are emulated. The authors of [8], [29] have acknowledged this limitation of their model, especially in micro-cells exhibiting a street guiding effect, where multiple bounces are common. In these cases, an effective street width is defined and applied to the ellipse, in order to render multiple bounces [30].

The usual geometry of GBSM is slightly modified in [31] to simulate macro-cells. In an attempt to model a N_p -tap PDS, the remote scatterers are distributed on N_p delay ellipses bearing different kinds of scatterers, extended ones, e.g. clusters, or single scatterers. Additionally, a circle of local scatterers is added around the UE. On the contrary, a circular exclusion area is drawn around the Node B. The scatterer density is fixed, but the number of scatterers is tuned versus the distance so as to reflect the experimental behaviour of channel parameters (K-factor, PDS, spatial correlation, etc.).

Most GBSM are single-bounce models, since they only account for a single specular reflection at the scatterer surface. Model [31], however, takes into account double bounces. An even more ambitious GBSM is presented in [32, ch. 9], where the received electro-magnetic field is derived from wave propagation results. The core of the model is the computation of a scattering dyad⁸ \vec{S}_l which models the interaction between the electro-magnetic field and the surfaces. Using this dyad, the channel coefficients of a narrowband MIMO transfer matrix $\mathbf{H}(t)$ write

$$h_{i,j}(t) = \sum_{k=1}^{N_g} \frac{e^{-j\omega\tau_k}}{(|\vec{r}_{j,s_k}| \star |\vec{r}_{s_k,i}|)^\gamma} G_{Tx}(\vec{r}_{j,s_k}) G_{Rx}(-\vec{r}_{s_k,i}) \vec{g}_{Rx}(-\vec{r}_{s_k,i}) \vec{S}_k \vec{g}_{Tx}(\vec{r}_{j,s_k}) \quad (1)$$

with N_s scatterers. τ_k , $\vec{r}_{a,b}$, $G(\vec{r}_{a,b})$ and $\vec{g}(\vec{r}_{a,b})$ stand respectively for the propagation delay, the vector joining a and b , the radiation pattern in the given direction and the orientation of the electro-magnetic field. The factor γ determines the attenuation of the waves. Finally, the operator \star represents either the

⁸In matrix formalism, a dyad is the outer product of two column vectors, as shown in (8).

product or the sum of the modulus of its arguments, depending whether scattering or specular reflection dominates.

B.2 Parametric stochastic models

Parametric Stochastic Models (PSM) describe the received signal as a superposition of waves. A common implementation of these models takes the form of a tapped delay line, where each tap reflects a propagation path.

The Double Directional Channel Model (DDCM) [10] is an example of a PSM. Its parameters can be given as a delay-angle distribution or through a spatial scatterer distribution [26, p. 155]. In [10], the DDCM is implemented as a tapped delay line model, where each of the N resolvable multipath components has got its own complex gain, delay, and (DoD, DoA) pair, regardless of the number of bounces. Both Tx and Rx antenna characteristics are excluded. Mathematically, the DDCM can therefore be described as [33]

$$\begin{aligned} \mathbf{H}(t, \tau, \phi_{Tx}, \theta_{Tx}, \phi_{Rx}, \theta_{Rx}) \\ = \sum_{k=1}^N \xi_k(t) \delta[\phi_{Tx} - \phi_{Tx,k}(t)] \delta[\theta_{Tx} - \theta_{Tx,k}(t)] \\ \delta[\phi_{Rx} - \phi_{Rx,k}(t)] \delta[\theta_{Rx} - \theta_{Rx,k}(t)] \\ \delta[\tau - \tau_k(t)], \end{aligned} \quad (2)$$

where $\delta(\cdot)$ is the delta function, ϕ stands for the azimuth and θ for the elevation. ξ is a 2×2 matrix whose elements are the complex gain of the orthogonal polarisations and the cross-coupling between polarisations.

Reference [34] introduce another flavour of the DDCM. The wavefronts arriving within a given delay bin are collapsed into a space-time fading coefficient $\beta_{k,i,j}(t)$. Each impulse response is then defined as the sum of N_p convolutions of the channel coefficients with the pulse shaping filter response of the system

$$h_{i,j}(t, \tau) = \sum_{k=1}^{N_p} c_{k,i,j}(t) g(\tau - \tau_{l,i,j}), \quad (3)$$

where the channel coefficients $c_{k,i,j}(t)$ include the path loss, the shadow fading and the space-time fading $\beta_{k,i,j}(t)$. The latter is defined as the superposition of L incoming local scattering wavefronts, and is given by

$$\beta_{k,i,j}(t) = \frac{1}{\sqrt{L}} \sum_{l=0}^{L-1} s_i(\phi_{Tx}^{k,l}) s_j(\phi_{Rx}^{k,l}) \nu_{k,l} e^{2j\pi f_{at} \cos(\phi_{Tx}^{k,l})}, \quad (4)$$

where \mathbf{s} is the steering vector of an Uniform Linear Array (ULA) and $\nu_{k,l}$ stands for the attenuation. Such a model, called Virtual Ray Model (VRM), has been proposed as system-level model for 3GPP [35]. For a 4×4 set-up, $L = 400$ is recommended.

B.3 Correlation-based stochastic models

Assuming the channel coefficients to be complex Gaussian-distributed, first and second order moments fully characterise the statistical behaviour of the channel. This has led to the development of several models based on the second order statistics of the MIMO channel.

Analysing the propagation of the waves in a single-bounce GBSM, one comes to the conclusion that the spatial correlation of the wavefronts can be characterised independently at the connection terminations [27], [28]. The correlation among the receiving elements is independent of the transmitter. Conversely, the correlation properties at the transmitter do not depend on the receiver.

A narrowband correlation-based model was proposed in [36] and filed in 3GPP as [37]. It can easily be extended to a wide-band perspective [38]

$$\mathbf{H}(\tau) = \sum_{k=1}^{N_p} (\mathbf{R}_{Rx}^k)^{\frac{1}{2}} \mathbf{A}^k (\mathbf{R}_{Tx}^k)^{\frac{1}{2}} \delta[\tau - (k-1)\Delta\tau], \quad (5)$$

where \mathbf{R}_{Tx}^k and \mathbf{R}_{Rx}^k are the spatial correlation matrices of the k^{th} tap, at the transmitter and at the receiver respectively, capturing the spatial correlation properties seen from these ends. On the other hand, \mathbf{A}^k is a matrix of independent, circularly symmetric complex Gaussian random variables.

The ability to define the global spatial correlation properties of the MIMO channel from the correlation coefficients independently derived at each end of the link relies on the assumption that the spatial correlation between antenna elements is a result of the scattering in their immediate surrounding areas. Consequently, the correlation between two paths is assumed to be the product of the correlation between the antennas connected by these paths at each end [39]. Generalising this assumption to the whole MIMO system, [40] introduced a wideband correlation-based model where the spatial correlation properties of a MIMO system are derived from a Kronecker product of the separately defined spatial correlation matrices \mathbf{R}_{Tx} and \mathbf{R}_{Rx} . The matrix decomposition of this product delivers a shaping matrix \mathbf{C} which multiplies a column vector of independent fading samples \mathbf{a} to emulate spatial correlation. Mathematically, using the $vec(\cdot)$ operator to reshape a matrix into a column vector, each channel coefficient can be written

$$vec(\mathbf{H}) = \mathbf{C} \mathbf{a}, \quad (6)$$

where, with the help of the Kronecker product operator \otimes , the channel correlation matrix \mathbf{R} is given by

$$\mathbf{R} = \mathbf{R}_{Tx} \otimes \mathbf{R}_{Rx} = \mathbf{C} \mathbf{C}^H. \quad (7)$$

The use of a Kronecker product to derive the global correlation properties of the MIMO system has been analytically demonstrated in [16] and further validated in [41] using least squares Kronecker factorisation. This correlation model has also been validated against measurement results in a narrowband perspective [16]. Its extension to polarisation diversity is presented in [42]. Finally, this model is the core of the 3GPP link-level MIMO model proposal [43].

The interest for correlation-based models came from the fact that they seem to give a more direct insight in the capacity increase of the MIMO systems, since they are based on \mathbf{R} . A direct link is therefore established between the rank of \mathbf{R} and the capacity increase. The more decorrelated the channel is,

the higher the ideal capacity [1] it would achieve. However, a counter-example has been identified, called pin-hole [44] or keyhole [45]. It does not deliver the promised capacity increase despite exhibiting spatially uncorrelated fading at both connection terminations, because its transfer matrix \mathbf{H} is rank-deficient. It is believed that such a behaviour could be experienced in hallways, tunnels, or for very large distances between the UE and Node B. In these waveguide-like situations, the authors of [46] have shown that the rank deficiency was due to the electro-magnetic characteristics of the propagation environment. The limitation of the number of possible propagation modes in waveguides is leading to a reduction of the multiplexing gain⁹. The pin-hole/keyhole can be modelled by defining its MIMO transfer matrix \mathbf{H} as a dyad:

$$\mathbf{H} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} \begin{pmatrix} a_1 & a_2 \end{pmatrix} = \begin{pmatrix} a_1 b_1 & a_2 b_1 \\ a_1 b_2 & a_2 b_2 \end{pmatrix}. \quad (8)$$

An improved model was proposed in [44] aiming at designing a MIMO model that would account for these special wave guiding cases as well. It claims to model separately the diversity gain of the MIMO channel, related to the spatial decorrelation of the fading, and its multiplexing gain, associated with the rank of the transfer matrix. From a geometrical perspective, this model assumes the existence of two clouds of near-field scatterers, defined as ideal reflectors, surrounding the connection terminations. These clouds account for the spatial correlation properties observed from the transmit and receive antennas. This correlation information is collected by a pair of matrices (\mathbf{R}_{Tx} , \mathbf{R}_{Rx}). Additionally, the correlation properties of the propagation paths between the two clouds of scatterers are modelled in a third matrix \mathbf{R}_s which impacts on the rank of the whole system, and therefore controls its multiplexing gain. The narrowband transfer matrix is therefore given by

$$\mathbf{H} = (\mathbf{R}_{Rx})^{\frac{1}{2}} \mathbf{A}_r (\mathbf{R}_s)^{\frac{1}{2}} \mathbf{A}_t (\mathbf{R}_{Tx})^{\frac{1}{2}}, \quad (9)$$

where the elements of matrices \mathbf{A}_t and \mathbf{A}_r are complex Gaussian distributed. Hence, each element of \mathbf{H} is double Rayleigh¹⁰ distributed, as suggested in [45]. In this approach, the rank of the MIMO system depends on the ranks of three correlation matrices. Hence, despite having uncorrelated antenna elements and therefore full-rank \mathbf{R}_{Tx} and \mathbf{R}_{Rx} , one could experience a low rank channel due the low Scatterer-To-Scatterer (STS) rank of matrix \mathbf{R}_s . Reference [47] discusses the impact of the STS on the capacity. Note that a similar, first-order model, called Geometric Based MIMO Channel Model with Keyholes (GBCMK) has been proposed in [48]. It introduces a transfer matrix which connects transmitted waves to received ones through a diffracting slit.

C. Link- versus system-level models

Most of the models listed so far mainly account for the small-scale characteristic of MIMO radio channels. Pathloss, shadow

⁹Gain provided by the exploitation of parallel, orthogonal subchannels in MIMO systems [44].

¹⁰To be understood as the product of two Rayleigh-distributed random variables.

fading and birth-death of taps are rarely modelled, although some proposals like [49] have been made. This choice is motivated by the fact that performance studies of cellular networks are commonly realised at two distinct simulation time resolutions. The lowest resolution, at bit/link level, is mostly impacted by the small-scale, fast-fading phenomena. On the other hand, the highest resolution, at system/frame level, evaluates the incidence of large-scale variations, including other-cell interference, over a typical time span of several minutes. This double-level approach is documented in [50, ch. 10] and has been adopted within 3GPP. It has led to the definition of two models, a link-level [43] and a system-level [51].

III. MULTIPLE ANTENNA PROCESSING FOR UMTS FDD DOWNLINK

Until today, many ideas have emerged trying to make efficient use of the radio spectrum allocated to the UMTS. Among those, multiple antenna element schemes appear to have high potential and are considered in current 3GPP standardisation work.

As downlink traffic is expected to dominate, the following will point out some of the difficulties associated with practical schemes proposed for the UMTS FDD downlink [50] and select promising schemes under specific system conditions.

A. Considerations when choosing a multiple element scheme

From a manufacturer's point of view, a scheme gains attractiveness for the downlink if the extra costs and complexities (e.g. an antenna array at the Node B instead of a single antenna) are low compared to the introduced performance gains [52]. Furthermore, it is attractive if the additional hardware can be reused to also facilitate uplink enhancements.

In UMTS all user signals are simultaneously sent out from the Node B on the same carrier frequency but separated in the code domain by orthogonal Walsh-Hadamard spreading codes. These signals reach the receiver through a time dispersive channel. If the UE uses a standard RAKE receiver, time dispersion results in a loss of orthogonality between the users' spreading codes and therefore in own-cell Multiple Access Interference (MAI). Equalisation can be used to restore orthogonality between the users whose signals propagate through the same radio channel (including transmit antenna weights) but is often complicated when multiple transmit antenna element schemes are deployed.

In general, the gain from multiple antenna element diversity schemes diminishes, when other forms of diversity are also available. Other diversity sources could for example be frequency diversity, time diversity (e.g. automatic retransmission request), soft handover diversity or site selection transmit diversity.

All schemes proposed so far for the 3GPP UMTS FDD standard include coherent signal detection. Hence, the receiver needs Channel State Information (CSI) for the decoding process. This is gained from decoding pilot signals sent from the Node B. Additionally, some schemes make use of dedicated pilot sequences. Introducing more transmit antenna elements might require that more radio propagation channels have to be estimated by the use of pilot signals or sequences. Thus, a higher portion

of the overall power might have to be dedicated to pilot assisted channel estimation. Nevertheless, the inherent pilot overhead must be kept small compared to the potential performance benefit of a multiple element system.

The amount and quality of CSI available to the transmitter will have a major impact on multiple element scheme performance. In a practical UMTS FDD system, the channel is time varying. By employing uplink channel estimates and a priori knowledge of the propagation differences between uplink and downlink channels, an indirect indication of the average downlink CSI can be obtained. Quasi-instantaneous channel knowledge at the transmitter can only be acquired through receiver feedback. As the available feedback bandwidth is limited more accurate CSI is available to the transmitter when the channel is slowly time varying, i.e. for low mobile speeds. When the channel is varying very fast, i.e. high mobile speeds, less CSI is available to the transmitter. Additionally, during the feedback round trip delay, the channel may have changed significantly before the transmitter can use the received CSI. Finally, the CSI available at the transmitter might suffer from transmission errors and incorrect detection.

The performance of multiple element systems depends also considerably on the correlation properties between the antenna elements. The distance required to achieve spatial decorrelation between antenna elements depends on the scattering environment (DoD, DoA and AS). High AS leads to low correlation between closely spaced antenna elements [53]. In many outdoor scenarios the antenna element correlation at the Node B is therefore higher than at the UE. Decorrelation, however, cannot only be achieved by spatial separation but also by different polarisations of the antenna elements.

The Multiple-Input Single-Output (MISO) and MIMO schemes proposed for the UMTS FDD downlink can be grouped into four major categories: Closed Loop Transmit Diversity (CLTD), Conventional Beamforming (CBF), Open Loop Transmit Diversity (OLTD) and code reuse.

B. Closed Loop Transmit Diversity

All CLTD schemes utilise quasi-instantaneous CSI, which is fed back to the transmitter on the uplink control channel¹¹. The transmit weights are chosen to maximise the signal power at the receiver. Different closed loop schemes can be applied to adapt to the changing radio channel at different terminal speeds while the available CSI feedback bandwidth remains unchanged. These schemes differ mainly in their degree of antenna weight resolution. Antenna weight adjustment is ranging from a simple "on/off" in Selection Transmit Diversity (STD) [55] for higher terminal speeds, over phase and amplitude adjustment in Rel. 99/4 Mode 1/2 [54]¹², to eigenbeam selection and eigenbeam combining techniques [56] for slower moving terminals.

Generally, it can be said that CLTD schemes can perform well over a wide range of channel correlations. Nevertheless, their

¹¹In Rel. 99/4 on the Dedicated Physical Control Channel at 1 bit per slot (0.6 ms) [54].

¹²And their extensions to more than two Tx antennas [56].

diversity gain will decrease with increasing correlation. Additionally performance will degrade with an increase of terminal speed and radio channel frequency selectivity [57, ch. 6].

C. Conventional Beamforming

In CBF [58], the set of coefficients applied at the antenna array of Node B are selected in order to steer a directional beam towards the served user. The process of steering this beam aims at concentrating the transmitted energy at the azimuth location of the desired user, therefore decreasing the degree of interference that this signal is causing to other users located at different azimuth directions. This kind of spatial interference filtering leads to an increase of the experienced Signal-to-Interference-plus-Noise Ratio at the UE and, thus, increases the system capacity [59].

The only CSI that is needed for pointing a beam towards a certain azimuth direction is the DoA of the user, which can be estimated from the uplink channel due to the reciprocal behaviour of up and downlink [60]. When generating the beams, there are two options:

- to allow beam steering towards a continuous set of azimuth directions (continuous beamforming) [61]
- or
- to generate a fixed grid of beams, from which the one with the highest gain towards the user is selected [62], [63].

The first option gives a better match between the azimuth location of the user and the azimuth direction pointing the beam in. However, since the number of possible beams is very large, it is not affordable (in terms of pilot power overhead) to transmit a common pilot signal per beam. Therefore, users are forced to perform channel estimation based on dedicated pilots. This leads to subsequent performance degradation compared to the case in which a common pilot is used. The reason for this is that the effective experienced radio channel is affected by the set of weights applied at the antenna array. Thus, the utilised pilot signal must be transmitted with the same weights as the data signal to be received with those channel estimates.

Due to the finite number of beams in the second option (fixed grid of beams), the deployment of a common pilot channel per beam is affordable. The performance is increased compared to the case in which channel estimation is based on dedicated pilot signals. This can counteract the performance degradation due to a potential mismatch between the azimuth direction of the user and the direction at which the beam is pointed. Furthermore, a fixed beam grid scheme is a simpler solution than continuous beamforming and requires less accurate DoA estimation. For the aforementioned spatial filtering capabilities to be effective, the azimuth dispersion of the radio channel has to be low, corresponding to high correlation between the antenna elements [64]. Moreover, CBF can be combined with transmit diversity when the polarisation domain is exploited [65].

D. Open Loop Transmit Diversity

If no CSI is available at the transmitter, it is possible to transmit from the antenna elements using space-time block encoded signals relying on the introduced diversity to improve the effective channel quality. The simplest scheme is Time Switching

Spatial correlation UE speed	Very high	High		Medium and low		
	All	Medium and high	Low	High	Medium	Low
Favourite scheme	Fixed grid of beams	Fixed grid of beams (possibly in combination with polarisation STTD)	Fixed grid of beams (possibly in combination with CLTD in the polarisation domain)	<ul style="list-style-type: none"> • Eigenbeam-STTD • STTD • Polarisation STTD 	<ul style="list-style-type: none"> • Eigenbeam Selection • CLTD mode 1 and extensions to more than 2 Tx antennas 	<ul style="list-style-type: none"> • Eigenbeam Combining • CLTD mode 2 and extensions to more than 2 Tx antennas

TABLE II

SELECTION OF FAVOURITE SCHEMES ACCORDING TO THE SPATIAL CORRELATION OF THE ENVIRONMENT AND THE MOBILE SPEED

Transmit Diversity (TSTD), where the signal is transmitted alternatively from different antennas ([54], [66]). More sophisticated solutions like STTD¹³ [54], STTD-OTD¹⁴ [67] and 4-Tx STTD [68] are based on orthogonal space-time block codes [69], [70]. Transmitting without any CSI is naturally sub optimal, but is sometimes the only practicable solution at high mobile speeds and in spatially uncorrelated environments. OLTD only works effectively if sufficient decorrelation is available between the transmit diversity branches. If STTD as specified in [54] is used in a highly time dispersive environment orthogonality between the users' spreading codes and additionally, orthogonality between the space-time codes is lost [71] and re-orthogonalisation is not straightforward.

E. Code reuse

Code reuse differs from the previous schemes, as it does not primarily depend on the amount of CSI at the transmitter but on decorrelation of the antenna elements. Closed loop and open loop code reuse schemes exist. Generally, code reuse schemes transmit with the same spreading and scrambling code from different antenna elements. The receiver uses iterative signal detection (e.g. a minimum mean square error detector) and interference cancellation to decode the different signals. The first open loop schemes were proposed by Lucent (D-BLAST¹⁵ [72], V-BLAST¹⁶ [73]) and, in the UMTS context, led to the closed loop PARC¹⁷ method [74]. Other open loop code reuse schemes like Twisted STTD [75] and Double STTD [76] add a space-time block coding component to introduce diversity to the system. All code reuse schemes require non-linear receivers. Code reuse schemes performance is often assessed using the single user throughput metric [77]. Simulation results for frequency flat fading channels given in [75], [76], [78], [79] assume that a dominant portion of the Node B transmission power as well as most of the code resources are dedicated to a single user.

F. Favourite scheme selection

A brief enumeration of multiple antenna element schemes proposed for the downlink of UMTS FDD systems has been conducted and is summarised in Figure 2. The frequency selectivity and the correlation of the propagation environment as well as the amount and quality of transmitter CSI are the main factors influencing the multiple antenna element scheme performance.

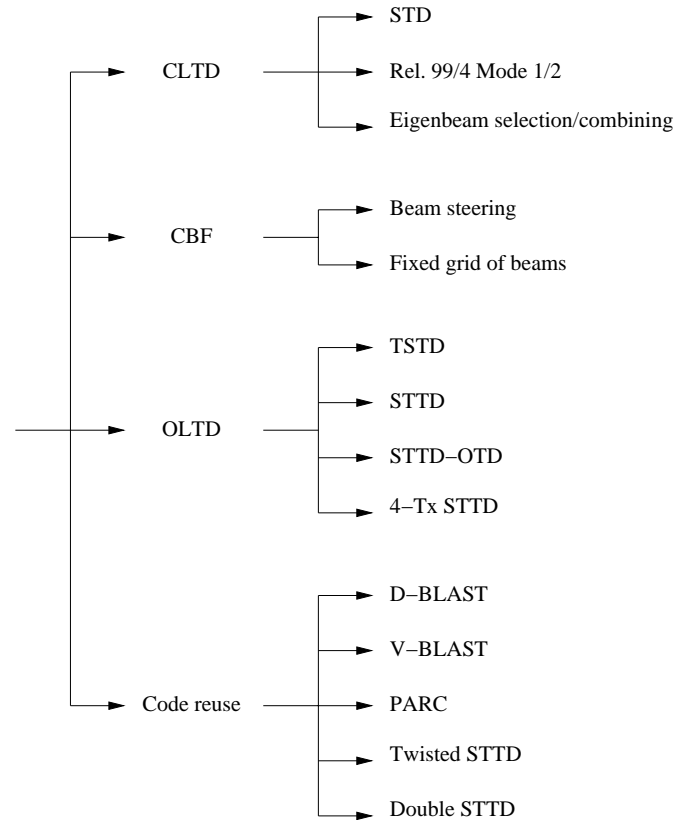


Fig. 2. Multiple antenna schemes proposed for UMTS FDD downlink

In the UMTS FDD downlink context, code reuse scheme proposals have mainly been limited to frequency flat fading scenarios. Moreover, they aim at maximising peak data rates for a single user rather than increasing system capacity. Therefore

¹³Space-Time Transmit Diversity.

¹⁴STTD-Orthogonal Transmit Diversity.

¹⁵Diagonal-Bell Labs Layered Space-Time.

¹⁶Vertical-Bell Labs Layered Space-Time.

¹⁷Per Antenna Rate Control.

they are not considered in the following selection of favourite schemes.

Assuming that the radio environment is only slightly frequency selective, e.g. ITU Pedestrian A profile [6], favourite schemes can be selected based on the spatial correlation of the environment and the UE speed, as shown in Table II.

In frequency selective environments, it has to be distinguished if RAKE receivers are used or if the UE attempts to equalise the channel. In the first case, all selected schemes suffer from the loss of orthogonality between the users' spreading codes. STTD based schemes might suffer additionally due to the fact that the orthogonal properties of the used space-time block code can not be preserved. These should therefore be used with care. The selection process of the other schemes as given in Table II remains unchanged. The process might change significantly, however, when using equalisation. With the help of an equaliser orthogonality between different users' spreading codes might be restored. This avoids own-cell MAI to some degree. Applying different transmit antenna weights for different users can increase the complexity of the equalisation problem. A selection of favourite schemes when equalisation is applied remains therefore as an open issue for further research.

IV. CONCLUSIONS

In this paper, an overview of recent developments in the study of multiple antenna systems possibly applicable in the framework of the 3GPP UMTS standard has been presented. The first part of the paper surveyed modelling activities of MIMO radio channels. Both deterministic and stochastic models have been addressed, and the link- and system-level model candidates in 3GPP have been identified. Following this survey, advanced schemes designed for multiple antenna systems in UMTS FDD downlink have been presented and discussed.

V. ACKNOWLEDGEMENTS

The authors thank Jean Philippe Kermaol for his fruitful comments. The authors also acknowledge financial support of the European Commission under the IST-2000-30148 I-METRA project and of Nokia Networks.

REFERENCES

- [1] I. E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," tech. rep., AT&T Bell Labs, June 1995.
- [2] U. Martin, J. Fuhl, I. Gaspard, M. Haardt, A. Kuchar, C. Math, A. F. Molisch, and E. Bonek, "Model Scenarios for Direction-Selective Adaptive Antennas in Cellular Mobile Communication Systems - Scanning the Literature," *Wireless Personal Communications*, pp. 109–129, 1999.
- [3] R. B. Ertel, P. Cardieri, K. W. Sowerby, T. S. Rappaport, and J. H. Reed, "Overview of Spatial Channel Models for Antenna Array Communication Systems," *IEEE Personal Communications*, pp. 10–22, Feb. 1998.
- [4] "MIMO Simulations Considerations," Tech. Rep. 3GPP TSG R1-02-0558, Telia, Apr. 2002.
- [5] "COST 207 Digital Land Mobile Radio Communications - Final Report," tech. rep., COST 207 Management Committee, 1989.
- [6] ITU, "Recommendation ITU-R M.1225 - Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000," tech. rep., 1997.
- [7] A. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," *IEEE Journal on Selected Areas in Communications*, vol. 5, pp. 128–137, Feb. 1987.
- [8] L. Héroult, "Final Project Report," tech. rep., European IST-1999-10741 Project ASILUM, Feb. 2002.
- [9] T. Zwick, D. Hampicke, J. Maurer, A. Richter, G. Sommerkorn, R. Thomä, and W. Wiesbeck, "Results of Double-directional Channel Sounding Measurements," in *Proceedings of IEEE 51th Vehicular Technology Conference VTC 2000 Spring*, pp. 2497–2503, May 2001.
- [10] M. Steinbauer, A. F. Molisch, and E. Bonek, "The Double-Directional Channel Model," *IEEE Antennas and Propagation Magazine*, vol. 43, pp. 51–63, Aug. 2001.
- [11] R. Stridh and B. Ottersten, "Spatial Characterization of Indoor Radio Channel Measurements at 5 GHz," in *Proceedings of First IEEE Sensor Array and Multichannel Signal Processing Workshop, Boston, MA, USA, Mar. 2000*.
- [12] D. P. McNamara, M. A. Beach, P. Karlsson, and P. Fletcher, "Initial Characterisation of Multiple-Input Multiple-Output (MIMO) Channels for Space-Time Communication," in *Proceedings of 4th European Personal Mobile Communications Conference EPMCC 2001, Vienna, Austria, Feb. 2001*.
- [13] "Correlation Measurements: Variability, Wide Band and Narrow Band Effects," Tech. Rep. 3GPP TSG R1-01-0919, Motorola, Aug. 2001.
- [14] "Propagation Modeling for Multi-Antenna Simulations," Tech. Rep. 3GPP TSG R1-01-1221, Motorola, Nov. 2001.
- [15] S. Mayrargue (Editor), "Smart Antennas IST Cluster - Year 2000 Report version 2," tech. rep., France Telecom R&D, Dec. 2001.
- [16] J. P. Kermaol, L. Schumacher, K. I. Pedersen, and P. E. Mogensen, "A Stochastic MIMO Radio Channel Model with Experimental Validation." Accepted for publication to *IEEE Journal on Selected Areas in Communications*, Aug. 2002.
- [17] C. C. Martin, J. H. Winters, and N. R. Sollenberg, "Multiple-Input Multiple-Output (MIMO) Radio Channel Measurements," in *Proceedings of IEEE Vehicular Technology Conference VTC'2000 Fall, Boston, MA, USA, pp. 774–779, Sept. 2000*.
- [18] P. Kyritsi and D. C. Cox, "Propagation characteristics of horizontally and vertically polarized electric fields in an indoor environment: simple model and results," in *Proceedings of 54th IEEE Vehicular Technology Conference VTC 2001 Fall, Atlantic City, NJ, USA, vol. 3, pp. 1422–1426, Oct. 2001*.
- [19] J. Kivinen, P. Suvikunnas, D. Perez, C. Herrero, K. Kalliola, and P. Vainikainen, "Characterisation system for MIMO channels," in *Proceedings of 4th International Symposium on Wireless Personal Multimedia Communications WPMC'01*, pp. 159–162, Sept. 2001.
- [20] "MIMO Channel Measurement and Modeling Results," Tech. Rep. 3GPP TSG R1-01-1305, Qualcomm, Nov. 2001.
- [21] A. Klein and W. Mohr, "A Statistical Wideband Mobile Radio Channel Model Including the Directions-of-Arrival," in *IEEE 4th International Symposium on Spread Spectrum Techniques and Applications ISSSTA'96, Mainz, Germany, vol. 2, pp. 102–106, Sept. 1996*.
- [22] Q. H. Spencer, B. D. Jeffs, M. A. Jensen, and A. Lee Swindlehurst, "Modeling the Statistical Time and Angle of Arrival Characteristics of an Indoor Multipath Channel," *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 347–360, Mar. 2000.
- [23] "Recommended Delay Spread Models for HSDPA," Tech. Rep. 3GPP TSG R1-01-0890, Nortel Networks, Aug. 2001.
- [24] G. German, Q. Spencer, L. Swindlehurst, and R. A. Valenzuela, "Wireless indoor channel modeling: Statistical agreement of ray tracing simulations and channel sounding measurements," in *Proceedings of 26th IEEE International Conference on Acoustics, Speech and Signal Processing ICASSP 2001, Salt Lake City, USA, vol. 4, pp. 2501–2504, May 2001*.
- [25] A. G. Burr, "Evaluation of Capacity of Indoor Wireless MIMO Channel Using Ray Tracing," in *Proceedings of International Zürich Seminar IZS 2002, Zürich, Switzerland, pp. 28.1–28.6, Feb. 2002*.
- [26] L. Correia (Editor), *Wireless Flexible Personalised Communications - COST 259 Final Report*. John Wiley & Sons, 2001.
- [27] D.-S. Shiu, G. J. Foschini, M. J. Gans, and J. M. Kahn, "Fading Correlation and its Effect on the Capacity of Multielement Antenna Systems," *IEEE Transactions on Communications*, vol. 48, pp. 502–513, Mar. 2000.
- [28] "Proposal for a Unified Spatial Channel Model," Tech. Rep. 3GPP TSG R1-01-0722, Lucent, June 2001.
- [29] "Micro-cell Wideband Directional Channel Model," Tech. Rep. 3GPP TSG R1-01-0992, IMST GmbH, Nov. 2001.
- [30] A. M. Sayeed, "Modeling and Capacity of Realistic Spatial MIMO Channels," in *Proceedings of International Acoustics, Speech and Signal Processing Conference ICASSP'01*, vol. 4, pp. 2489–2492, 2001.
- [31] C. Oestges and A. J. Paulraj, "A Physical Model for Broadband MIMO Macrocell Channels." Accepted for presentation at 31st IEEE Communication Theory Workshop, Sanibel Island, FL, USA, May 2002.
- [32] T. Svantesson, "Antennas and Propagation from a Signal Processing Perspective, Ph.D. thesis," tech. rep., Chalmers University of Technology, Sweden, June 2001.

- [33] R. S. Thomä, D. Hampicke, A. Richter, and G. Sommerkorn, "Measurement and Identification of Mobile Radio Propagation Channels," in *Proceedings of IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary*, pp. 1163–1170, May 2001.
- [34] M. Stege, J. Jelitto, M. Bronzel, and G. Fettweis, "A Multiple-Input Multiple-Output Channel Model for Simulation of TX- and RX-Diversity Wireless Systems," in *Proceedings of IEEE Vehicular Technology Conference VTC 2000 Fall, Boston, MA, USA*, vol. 2, pp. 833–839, Sept. 2000.
- [35] "MIMO System Simulation Methodology," Tech. Rep. 3GPP TSG R1-02-0142, Lucent, Jan. 2002.
- [36] D. Chizhik, F. Rashid-Farrokhi, J. Ling, and A. Lozano, "Effect of Antenna Separation on the Capacity of BLAST in Correlated Channels," *IEEE Communication Letters*, vol. 4, pp. 337–339, Nov. 2000.
- [37] "Further link level results for HSDPA using multiple antennas," Tech. Rep. 3GPP TSG R1-00-1386, Lucent Technologies, Nov. 2000.
- [38] K. Yu, M. Bengtsson, B. Ottersten, D. McNamara, P. Karlsson, and M. Beach, "A Wideband Statistical Model for NLOS Indoor MIMO Channels." Accepted for presentation at IEEE Vehicular Technology Conference VTC'02 Spring, Birmingham, AL, USA, May 2002.
- [39] H. Asplund, A. A. Glazunov, A. F. Molisch, K. I. Pedersen, and M. Steinbauer, "The COST 259 Directional Channel Model - II. Macrocells." Submitted for publication in IEEE JSAC, Mar. 2001.
- [40] K. I. Pedersen, J. B. Andersen, J. P. Kermaol, and P. E. Mogensen, "A Stochastic Multiple-Input-Multiple-Output Radio Channel Model for Evaluation of Space-Time Coding Algorithms," in *Proceedings of IEEE Vehicular Technology Conference VTC'2000 Fall, Boston, MA, USA*, pp. 893–897, Sept. 2000.
- [41] K. Yu, M. Bengtsson, B. Ottersten, D. McNamara, P. Karlsson, and M. Beach, "Second Order Statistics of NLOS Indoor MIMO Channels Based on 5.2 GHz Measurements," in *IEEE Global Telecommunications Conference GLOBECOM '01, San Antonio, TX, USA*, vol. 1, pp. 156–160, Nov. 2001.
- [42] J. P. Kermaol, L. Schumacher, F. Frederiksen, and P. Mogensen, "Polarisation Diversity in MIMO Radio Channels: Experimental Validation of a Stochastic Model and Performance Assessment," in *Proceedings of IEEE Vehicular Technology Conference VTC 2001 Fall, Atlantic City, USA*, Oct. 2001.
- [43] "MIMO Discussion Summary," Tech. Rep. 3GPP TSG R1-02-0181, MIMO Rapporteur, Jan. 2002.
- [44] D. Gesbert, H. Boleskei, D. Gore, and A. J. Paulraj, "MIMO Wireless Channels: Capacity and Performance Prediction," in *Proceedings of Globecom 2000, San Francisco, USA*, vol. 2, pp. 1083–1088, Nov. 2000.
- [45] D. Chizhik, G. J. Foschini, and R. A. Valenzuela, "Capacities of Multi-Element Transmit and Receive Antennas: Correlations and Keyholes," *Electronics Letters*, vol. 36, pp. 1099–1100, June 2000.
- [46] D. Chizhik, G. J. Foschini, M. J. Gans, and R. A. Valenzuela, "Keyholes, Correlations, and Capacities of Multi-Element Transmit and Receive antennas," *IEEE Transactions on Wireless Communications*, vol. 1, pp. 361–368, Apr. 2002.
- [47] D. Gesbert, H. Bölckei, D. A. Gore, and A. J. Paulraj, "Performance Evaluation for Scattering MIMO Channel Models," in *Conference Record of 34th Asilomar Conference on Signals, Systems and Computers*, vol. 1, pp. 748–752, Oct. 2000.
- [48] A. Sibille, "Keyholes and MIMO Channel Modelling," COST 273 TD(01)017, ENSTA Paris, France, Oct. 2001.
- [49] M. Cabrera, J. Vidal, and O. Muñoz, "Time Evolutionary Wideband Propagation Channel Model for User Positioning in UMTS," in *Proceedings of IST Mobile Communication Summit 2001, Barcelona, Spain*, Sept. 2001.
- [50] H. Holma and A. Toskala, *WCDMA for UMTS - Radio Access for Third Generation Mobile Communications*. John Wiley & Sons, 2000.
- [51] "MIMO System Level Channel Model," Tech. Rep. 3GPP TSG R1-02-0548, Lucent, Apr. 2002.
- [52] J. Ylitalo, A. Pollard, M. Heikkilä, and J. R. Fonollosa, "Cost versus Benefit Trade-offs of Multi-Element Transmit and Receive," tech. rep., European IST-1999-11729 Project METRA, Aug. 2001.
- [53] J. Salz and J. Winters, "Effect of Fading Correlation on Adaptive Arrays in Digital Mobile Radio," *IEEE Transactions on Vehicular Technology*, vol. 43, pp. 1049–1057, Nov. 1994.
- [54] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, "Physical Channels and Mapping of Transport Channels onto Physical Channels (FDD)," Tech. Rep. TS 25.211 v3.1.1, Dec. 1999.
- [55] D. Rajan and S. D. Gray, "Transmit Diversity Schemes for CDMA-2000," in *Proceedings of the IEEE Wireless Communications and Networking Conference WCNC'99*, vol. 2, pp. 669–673, Mar. 1999.
- [56] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, "Tx Diversity Solutions for Multiple Antennas (Release 5)," Tech. Rep. TS 25.869 v0.2.0, Dec. 1999.
- [57] T. Klingenbrunn, "Downlink Capacity Enhancement of UTRA FDD Networks, Ph.D. thesis," tech. rep., Aalborg University, Denmark, Jan. 2001.
- [58] B. Van Veen and K. M. Buckley, "Beamforming: a Versatile Approach to Spatial Filtering," *IEEE Acoustics, Speech and Signal Processing Magazine*, vol. 5, pp. 4–24, Apr. 1988.
- [59] A. F. Naguib, A. J. Paulraj, and T. Kailath, "Capacity Improvement with Base Station Antenna Arrays in Cellular CDMA," *IEEE Trans. on Vehicular Technology*, vol. 43, pp. 691–698, Aug. 1994.
- [60] K. Pedersen, P. Mogensen, and F. Frederiksen, "Joint Directional Properties of Uplink and Downlink Channel in Mobile communications," *Electronics Letters*, vol. 35, pp. 1311–1312, Aug. 1999.
- [61] P. H. Lehen and M. Pettersen, "An Overview of Smart Antenna Technology for Mobile Communication Systems," *IEEE Communications Surveys*, vol. 2, no. 4, pp. 2–13, 2000.
- [62] M. Exicson, A. Osseiran, J. Barta, B. Goransson, and B. Hagerman, "Capacity Study for Fixed Multi Beam Antenna Systems in a Mixed Service WCDMA System," in *Proceedings of 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC 2001, San Diego, CA, USA*, vol. 1, pp. 31–35, Sept. 2001.
- [63] J. Ramiro-Moreno, K. I. Pedersen, and P. E. Mogensen, "Network Performance of WCDMA Base Stations Deploying Smart Antennas," in *Proceedings of 4th International Symposium on Wireless Personal Multimedia Communications WPMC'01*, vol. 2, pp. 1027–1032, Sept. 2001.
- [64] K. I. Pedersen, P. E. Mogensen, and B. H. Fleury, "Spatial Channel Characteristics in Outdoor Environments and their Impact on BS Antenna System Performance," in *Proceedings of IEEE Vehicular Technology Conference VTC 1998, Ottawa, Canada*, vol. 2, pp. 719–723, 1998.
- [65] K. I. Pedersen and P. E. Mogensen, "A Simple Downlink Antenna Array Algorithm Based on a Hybrid Scheme of Transmit Diversity and Conventional Beamforming," in *Proceedings of 53rd IEEE Vehicular Technology Conference VTC 2001 Spring, Rhodes, Greece*, vol. 1, pp. 58–62, May 2001.
- [66] A. Hottinen and R. Wichman, "Transmit Diversity by Antenna Selection in CDMA Downlink," in *Proceedings of IEEE 5th International Symposium on Spread Spectrum Techniques and Applications ISSSTA'98, Sun City, South Africa*, vol. 3, pp. 767–770, Sept. 1998.
- [67] "STTD-OTD Open-Loop Transmit Diversity Scheme for HSDPA Systems with Four Transmit Antennas," Tech. Rep. 3GPP TSG R1-01-0578, Texas Instruments, Feb. 2001.
- [68] "Text proposal for 4-Tx-STTD (TR25.869)," Tech. Rep. 3GPP TSG R1-02-0270, Nokia, Jan. 2002.
- [69] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1451–1458, Oct. 1998.
- [70] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-Time Block Coding for Wireless Communications: Performance Results," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 451–460, Mar. 1999.
- [71] M. Lenardi, A. Medles, and D. T. Slock, "Capacity Study for Fixed Multi Beam Antenna Systems in a Mixed Service WCDMA System," in *Proceedings of 2001 IEEE International Conference on Communications ICC'01, Helsinki, Finland*, vol. 6, pp. 1679–1683, June 2001.
- [72] G. J. Foschini, "Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas," *Bell Labs Technical Journal*, vol. 1, no. 2, pp. 41–59, 1996.
- [73] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An Architecture for Realizing Very High Data Rates over the Rich-Scattering Wireless Channel," in *Proceedings of International Symposium on Advanced Radio Technologies, Boulder, CO, USA*, Sept. 1998.
- [74] S. T. Chung, A. Lozano, and H. C. Huang, "Approaching Eigenmode BLAST Channel Capacity Using V-BLAST with Rate and Power Feedback," in *Proceedings of IEEE Vehicular technology Conference VTC 2001 Fall, Atlantic City, NJ, USA*, vol. 2, pp. 915–919, Sept. 2001.
- [75] O. Tirkkonen and A. Hottinen, "Improved MIMO Performance with Non-Orthogonal Space-Time Block Codes," in *IEEE Global Telecommunications Conference GLOBECOM '01, San Antonio, TX, USA*, vol. 2, pp. 1122–1126, Nov. 2001.
- [76] "Double-STTD Scheme for HSDPA Systems with Four Transmit Antennas: Link Level Simulation Results," Tech. Rep. 3GPP TSG R1-01-0458, Texas Instruments, Feb. 2001.
- [77] "MIMO Simulation Methodology for Single-User Throughput," Tech. Rep. 3GPP TSG R1-01-0880, Lucent, June 2001.
- [78] "Increasing MIMO Throughput with Per-Antenna Rate Control," Tech. Rep. 3GPP TSG R1-01-0879, Lucent, June 2001.
- [79] "Comparison Between TxAA/STTD and PARC for HSDPA Systems with 2 Transmit Antennas," Tech. Rep. 3GPP TSG R1-01-1064, Texas Instruments, Nov. 2001.