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Deliverable D4.1.1

Reconfigurable IA/MIMO Transceiver Algorithms

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Abstract:

In this deliverable the concepts, design criteria and performance evaluation of reconfigurable multiple antenna techniques are discussed. First, channel modelling approaches suitable for the scenarios investigated in MEMBRANE are explored and the studies framework is established, in terms of link and system level performance evaluation methodologies, physical layer parameters and critical performance metrics. Then, reconfigurable multiple antenna techniques are described, designed to exploit channel state information and adapt to varying propagation and network conditions. Finally, scheduling and routing considerations are discussed.

Keyword list: Intelligent Antennas (IA), MIMO, channel model, link level performance, system level performance, reconfigurable transceivers, channel state information, space-time block coding, beamforming, spatial multiplexing, Space Division Multiple Access

EXECUTIVE SUMMARY

In this report, in order to establish the framework for the reconfigurable multiple antenna studies in MEMBRANE, we propose some channel models for different scenarios and determine some physical layer parameters. We also give a general description on some strong candidates on multiple antenna technologies.

First, difference scenarios along with their corresponding parameters are studied. The scenarios are categorized into the Urban and Rural areas. Three sub-categories (namely U1, U2, U3) and 2 sub categories (namely R1, R2) are identified for the MEMBRANE Project. Different channel models are then selected to model these different scenarios respectively. Models from WINNER Project and 3GPP/3GPP2 are selected and will be modified for the corresponding scenarios.

Furthermore, the interference in a multi-hop wireless backhaul network is studied, and a ‘regular’ network topology with hexagonal cells is proposed to model the interference, where the Access Node is surrounded by rings of Intermediate Nodes. Assuming that only the nodes on adjacent rings can communicate with each other, we suggest to only consider the first ring of strongest interferers that communicates simultaneously as the interference.

Then, we propose some parameters and performance metrics for the physical layer. Both the system parameters and scenario parameters are given in this report, which setup the system framework for future research. The performance metrics are discussed on both the link level and system level. Different metrics are proposed and will be used to test different algorithms developed in the MEMBRANE Project.

In this report, a number of multiple antenna techniques are described. Details on MIMO transceiver architecture, intelligent antennas, space-time coding, spatial multiplexing and Opportunistic Beamforming are presented. These are the strong candidates for our future research. Moreover, we propose two multiple antenna baseline techniques for the MEMBRANE Project.

Finally, we discuss the scheduling and routing in a wireless backhaul network. We point out that the main target for scheduling and routing is to avoid the interference while at the same time maximizing the throughput and minimizing the delay. Spatial scheduling, spatial routing and adaptation are briefly described at the end of this report.

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1 INTRODUCTION

This deliverable analyses the concepts and design criteria of novel reconfigurable multiple antenna algorithms for efficient signalling in different propagation scenarios of the multihop wireless backhaul network considered in MEMBRANE.

The primary aim of the reconfigurable transceivers design is to optimise the performance of each individual multi-antenna wireless link, taking into account varying propagation, traffic and backhaul multihop network topology conditions. To this end, a number of adaptive antenna system architectures will be considered, such as multiple input multiple output (MIMO) transceivers, space-time coding, interference-robust techniques and cross-layered optimised array processing, such as opportunistic beamforming.

To set the ground for the design and analysis of reconfigurable multiple antenna transceivers, the **channel characterisation and modelling** for different scenarios studied in MEMBRANE will be first discussed, especially in view of the three different types of propagation channels associated with the multihop wireless backhaul topology (Access Node (AN)-to-Intermediate Node (IN), IN-to-IN and IN-to-End Node (EN)). The selection of suitable antenna configurations and associated algorithms is also affected by the geographic terrain, wherein the radio network operates. The investigation of the relevant state-of-the art in channel modelling will reveal that there are still a number of open questions in the propagation and channel of the multiple antenna multihop wireless backhaul. For its initial studies, MEMBRANE will rely on the latest developments in standardisation (e.g. IEEE 802.16x) and other research projects (e.g. IST WINNER).

The **interference modelling** issue will be briefly addressed, especially with respect to the wireless backhaul specifics. Interference in wireless backhaul results from two main sources: multiple access-type of interference, when a node is simultaneously receiving from multiple neighbouring nodes, and ‘inter-node’ interference caused by transmissions using the same sub-channel over two separate links. It is important to note that although the nodes are in general fixed in a backhaul set up, the activation of different links resulting from adaptive routing and scheduling decision may result in rapidly varying interference conditions.

In the second part of the deliverable, basic **spatial processing approaches** for the optimisation of a single link will be discussed, namely intelligent antennas, space-time coding, spatial multiplexing and interference cancellation. Novel **reconfigurable designs** will then be presented, which enhance the performance of the basic spatial processing techniques through the exploitation of the Channel State Information (CSI). A multiple antenna transceiver is classified as reconfigurable when it achieves (close to) optimal performance independent of a certain parameter variation that may improve or degrade a basic spatial processing technique. Spatial correlation, which is a function of the propagation characteristics and the antenna array geometry, may be used as an example to explain the concept of reconfigurability: spatial correlation may be harmful for techniques exploiting spatial diversity but beneficial for techniques relying on spatial coherence. A reconfigurable technique would always achieve the best of both worlds independent of the actual value of spatial correlation in a certain scenario.

While in the MEMBRANE backhaul network setup the wireless topology is fixed, giving a more static nature to interference, the transmitted data packet patterns will still vary in time; hence the developed interference cancellation techniques must take this into account. One important aspect that IA algorithms must be able to address is the varying network topology, due to the addition of new nodes (especially in the early stages of deployment) and / or the failure of existing nodes. Hence, the IA techniques must be re-configurable in this respect as well.

In the multi-user (multi-link) case, Space Division Multiple Access (SDMA) allows for transmission/reception of multiple data streams using the same time/frequency resources and exploiting the presence of a number of distinct spatial modes. Moreover, in the multihop backhaul case, the SDMA option may be jointly optimised with the scheduling and routing schemes and result in higher data rates and efficient resource management, which adapts to the network topology dynamics.

In a similar manner, cross-layer optimisation, i.e. combination of spatial processing with scheduling, takes advantage of multi-user (multi-link) diversity and exploits cross-layer information associated with Quality of Service (QoS) criteria.

The objective of this deliverable is to set the ground in terms of basic physical layer and channel modelling assumptions and present the major candidates for reconfigurable multiple antenna transceiver designs. Based on these designs, the studies on theoretical multihop network performance analysis performed in WP3 and the studies on scheduling, routing and power control performed in WP4.2, further work in this work package will focus on identifying the optimal topologies, in terms of spacing between relay nodes, frequency reuse patterns, suitable antenna array configurations and efficient reconfigurable transceiver modes to be deployed in the jointly optimised scheduling, routing and power control strategies.

The deliverable is organised as follows: In Chapter 2 the target scenarios and channel modelling options suitable for the MEMBRANE investigations are presented. Interference issues associated with the multihop wireless backhaul are discussed in Chapter 3 and the physical layer parameters to be considered in the studies in Chapter 4. The basic multiple antenna approaches along with techniques that achieve reconfigurability to varying propagation and network conditions are analysed in Chapter 5. Scheduling and routing considerations are addressed in Chapter 6. Finally the deliverable is concluded in Chapter 7.

2 SCENARIOS AND CHANNEL MODELS

2.1 Channel modelling implications of MEMBRANE scenarios

As analysed in [MEM D21] one of the main concerns of MEMBRANE is to enhance the presence of broadband in rural and remote zones, thus helping combat the "digital divide" between these areas and the big urban centres, caused mainly by the inadequacy (or even absence) of backhaul infrastructure and the requirement for fast and cost efficient deployment. Moreover, as user's necessities in the big urban centres become increasingly demanding, as a result of the large concentration of population around the major cities and the proliferation of a number of new data services, MEMBRANE is also addressing the problem of enhancing service provision in terms of coverage, capacity and QoS in densely populated metropolitan areas.

In view of the above objectives, [MEM D21] identified two target scenarios that will be used throughout the studies in MEMBRANE. For convenience, these are briefly reviewed below:

Rural target scenario: Usage examples considered in this scenario include the following three cases: i) IT professionals living in the country side, ii) labour workers who make use of internet technology and special applications to better manage their business (e.g. agriculture) and iii) seasonal tourists who need access to the local information, such as accommodation, entertainment etc. Rural remote areas are characterised by sparse population, large distances from urban centres and main communication hubs (airport, train stations etc), and *increased requirements in coverage and possible seasonal variation in capacity demands* (due for example to tourism).

Urban target scenario: This scenario concerns both the business sector and home user applications. With regards to the former, usage examples considered include office (big corporate organisations and small and medium size enterprises), industrial units, warehouses and shopping centres. Urban business areas are characterised by dense population and diverse building infrastructure, the existence of a number of hot spot areas (shopping and business centres, entertainment hubs, train stations etc.), and *increased demand in capacity that varies during the day/week/different seasons*.

Home usage examples include the domestic communication/entertainment activities, namely telephone, video-phone, broadband internet and television. The latter includes the latest applications offered by broadcast technologies (Digital Video Broadcasting-DVB). Residential areas are characterised by urban and suburban population density, and *increasing demand for better (more uniform) coverage and capacity,* resulting from the growing demand for broadband internet access at home.

When seen from the point of view of channel modeling for the multiple antenna multihop wireless backhaul network deployment, the above scenarios of interest possess the following general characteristics:

- An outdoor propagation environment is always met, since it is assumed that all backhaul nodes are deployed outside of buildings.
- Backhaul nodes are fixed (not moving);
- Nevertheless, there is still fading in the time domain due to the motion of scatterers surrounding the nodes.

Following, the backhaul network deployment characteristics of the aforementioned target scenarios are further elaborated. Based on this analysis, related propagation scenarios are eventually identified.

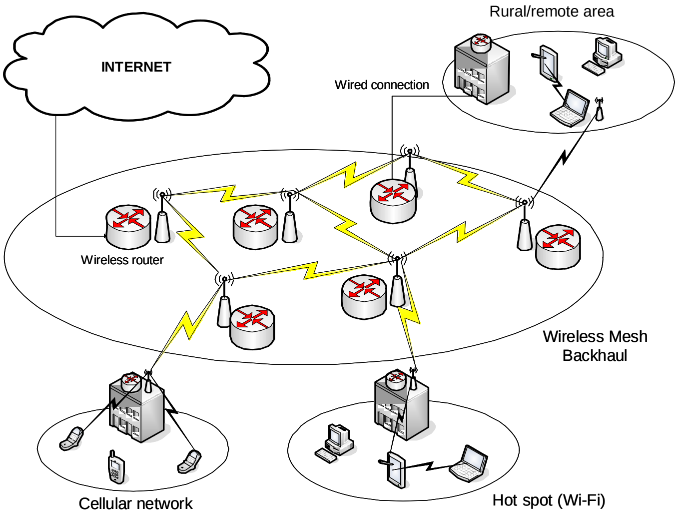

Figure 2.1 – MEMBRANE scenarios

2.1.1 Propagation in the urban target scenario

One fundamental characteristic of the MEMBRANE system is that it is designed to backhaul the traffic of macrocellular, microcellular and picocellular area access systems. Picocellular (hotspot in the WiFi terminology) access devices (WiFi access points, UMTS femtonodes, or a similar WiMAX potential device) are often installed by the client. On the other hand, wider area coverage Base Stations (BS) (WiMAX BSs or UMTS Node Bs) are carefully planned and installed by the operators.

In the picocellular case, some access device that incorporates MEMBRANE AN functionality is most likely to be mounted below-the-rooftop heights, for example at the side wall of a residence or a multiple story building. Alternatively, the AN might be found at the rooftop of a building providing access to the backhaul for the in-building users through wired or wireless connections.

For wide area access, a BS with AN functionality is typically located at high towers or at the rooftop of buildings. However, as the capacity demands increase, the BS is moving closer to the end user and it could be placed at below-the-rooftop heights.

Furthermore, in order to reduce deployment costs, MEMBRANE envisions that the INs interconnecting the ANs with the EN are mostly placed at moderate heights, in the order of 3-10 m – for example mounted on electrical poles, telephone poles or traffic lights. Still, it is possible that an IN is placed at rooftop height. Specifically, the case of high-placed AN logical units that incorporate IN functionality is particularly attractive.

Overall, the aforementioned node deployment strategy is substantially different from what is met in traditional backhauling solutions, in which nodes are exclusively mounted on high towers or at the rooftops of tall buildings and a clear line-of-sight (LOS) is required for reliable communication.

The implications of this type of deployment in channel modelling should be studied carefully. As a starting point, Table 2.1 classifies the various propagation scenarios that can be met in the MEMBRANE urban target scenario. Prioritized cases are marked in bold. Reference to the nodes being involved in a link is not made since in general, any MEMBRANE node (EN/IN/AN) can potentially be placed either above or below the rooftop level (although an EN is typically mounted on a tower or at the rooftop of a high building).

Table 2.1– Propagation scenarios in the urban case

#	Definition	LOS conditions	Maximum separation
U1	rooftop to rooftop	**LOS**	8 km
U2	below-rooftop to below-rooftop	**LOS** / **NLOS**	500 m
U3	rooftop to below-rooftop	LOS / **NLOS**	1 km

It is noted that the listed propagation scenarios could be separated in two subcases, depending on whether the building density is classified as urban or suburban. However, due to the scarcity of channel measurements for this kind of deployment, the MEMBRANE consortium has chosen to simplify the studies by focusing on the radio environment of a typical city centre. This case seems to be the most challenging one in terms of the capacity requirements of the backhaul network.

Propagation scenario U1: Rooftop to Rooftop

In this scenario both ends of a link are placed above the rooftop level. Pure LOS conditions are met as far as the first Fresnel zone is clear. This could be achieved by utilizing high towers, or by mounting the antennas on small towers that are installed at rooftops. Nevertheless, to reduce the potential deployment costs, we assume that antennas are 1-3 above rooftop level as illustrated in Figure 2.2. In this case Quasi-LOS conditions are met.

Propagation scenario U2: Below-rooftop to below-rooftop

This scenario concerns the case where both nodes are deployed below the surrounding buildings, at heights in the order of 3-10 m. This scenario covers both LOS and NLOS outdoor propagation conditions. Nodes are deployed in a Manhattan-like grid fashion. For any given node, the streets can be classified as the main street where the node is located, perpendicular streets and parallel streets. The LOS case is depicted in Figure 2.3.

Propagation scenario U3: Rooftop to below-rooftop

As illustrated in Figure 2.4, in this case the one end of the link is found above the rooftop level while the other is below that. This case possesses strong similarities with the traditional cellular case. The major differences are the Doppler spectrum shape and that a MEMBRANE node is placed at moderate heights. This might have an impact in various channel properties, such as path-loss, angle spread and delay spread. Although LOS conditions are possible, the NLOS case is more probable.

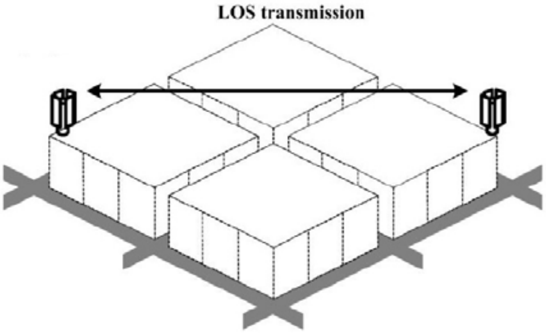

Figure 2.2 – LOS rooftop to rooftop link (source [16j-06/020])

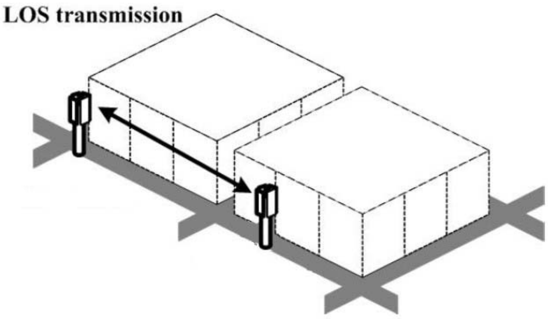

Figure 2.3 – LOS below rooftop to below-rooftop link

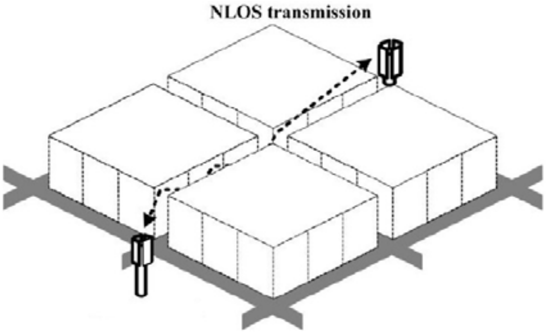

Figure 2.4 – NLOS rooftop to below-rooftop link (source [16j-06/020])

2.1.2 Propagation in the rural target scenario

A large number of remote small population centres are connected to the MEMBRANE mesh backhaul network. Each centre is surrounded by large agricultural areas. Population centres are quite distant from each other. Land is assumed to be relatively flat. Various vegetation patterns can be met. Essentially, the EN and INs are placed on high towers. In practice, the tower heights are selected such that the 1st Fresnel zone is clear and LOS conditions are met for the required link distance. Furthermore, the actual delay spread and angle spread due to propagation environment are effectively reduced due to the utilization of directional antennas with high gain. With regards to the AN, two cases might be distinguished. Firstly, the AN could be placed on a high tower. This is more likely when a wide area access technology is utilized, such as UMTS and WiMAX. In that case, the IN-AN and EN-AN links have similar properties with the EN-IN and IN-IN links. Secondly, the AN might be placed at some moderate height, for instance at an external wall or at the rooftop of a house. This is more likely where an AN incorporating a WiFi interface is installed by the customer without special care. In that case, LOS conditions are not guaranteed. Table 2.2 summarizes the aforementioned. Note that in scenario R2 the exact position of the AN, i.e. whether it is below the rooftop or at the rooftop of the residence / building, is not considered since the building infrastructure is sparse and the major scatterers are trees.

Table 2.2– Propagation scenarios in the rural case

#	Definition	Nodes A-B	A height	B height	LOS conditions	Maximum separation
R1	Planned infrastructure	all cases	high	high	**LOS**	30 km
R2	Non-planned links	EN-AN, IN-AN	high	moderate	**LOS / NLOS**	10 km / 5km

2.2 Fundamentals in spatio-temporal channel modelling

2.2.1 Introduction

Spatiotemporal or MIMO channel modelling adds to the challenge of representing realistically the propagation environment by introducing the requirements of accurately incorporating the spatial (angular) dimension. Channel models of this type can be classified broadly in two distinct categories:

- **Correlation-based channel models** are based on the statistical characterization of the matrix transfer function representation of the MIMO channel. The (i,j) entry in that matrix gives the SISO channel response from the i^{th} transmit to the j^{th} receive antenna element. As usual, this response can be represented by means of a tapped delay line that models the delay (frequency) domain characteristics of the corresponding SISO channel. To model the time (Doppler) domain properties of the channel, multiple independent realizations of each tap (that are corresponding to different time instances) are passed through a filter with a frequency response that accounts for the shape of the Doppler spectrum. The aforementioned procedure is repeated for all the entries of the matrix transfer function. The spatial domain is modelled by applying the so-called *correlation matrix* that models the correlation of the signal envelopes arriving at different elements of the receiver antenna array. This method relies on the statistical characterization of the delay, time and spatial domains that is deduced by evaluating measurement data. For this reason, the term *Stochastic* is frequently used in the literature for this type of models. However, this term is rather confusing and is avoided here because statistical means can be used in both categories.
- **Directional channel models** are based on a detailed reproduction of the channel ray structure. Each ray is characterized in terms of its complex amplitude, delay or time-of-arrival (ToA), direction-of-departure (DoD) and direction-of-arrival (DoA). To determine these parameters, various approaches exist. A *deterministic* approach can be followed when detailed environmental data is available (building geometry and construction materials, ground roughness and materials, e.t.c.). Since the propagation environment is known to a sufficient degree, wireless propagation is a deterministic process that allows full description of its characteristics at any given point in space. Furthermore, a *Geometry-based Stochastic* approach has been traditionally used, according to which the probability density function (pdf) of the geometrical location of the scatterers is prescribed. For each channel realisation, the scatterers' locations are taken at random from this pdf and then the ray delays and DoAs, DoDs and complex fadings can be evaluated. The determination of pdf relies on empirical assumptions regarding the scattering environment at the vicinity of the transmitter and the receiver. Last but not least, a *Stochastic* approach can be followed according to which measurement data can be used to characterize the statistical behaviour of the required parameters. As more data is becoming available, this approach is gaining ground. The terms *ray-based* and *physical* models are also used in the literature to name directional channel models. Moreover, the term *double-directional* is often used to stress that antenna arrays are utilized both at the transmitter and the receiver.

The most representative example of an analytical channel model is the well-known Stanford University Interim (SUI) model. This has been adopted in the past by the 802.16 standardization body [Erc01]. Analytic channel models for the indoor have been used in 802.11. On the other hand, 3GPP/3GGP2 has adopted the directional channel approach to develop the Spatial Channel Model (SCM) based on measurements [3GPP SCM]. This model has also been adopted by IEEE 802.20.

Both methods possess advantages and disadvantages. In essence, correlation models employ a more abstract view of the channel. As a result, they are simpler to design and less computationally intensive in the expense of some loss in accuracy. One practical advantage is that with this method, one can directly set the values of the correlation matrix. For these reasons, this method is very attractive for fast algorithm testing under several environments of various degrees of spatial selectivity / coherence. However, the lack of explicit parameterisation of the angular dimension makes this method unsuitable for certain techniques, such as beamforming. Last but not least, apart form the propagation environment, the correlation values depend also on the array elements' separation. In practical terms, this means, that specific correlation values observer in measurements are associated with the array geometry that was used in sounding.

On the other hand, the main advantage of directional channel models is that they are 'tailored' to a certain propagation environment and they can in principle accurately describe a certain propagation scenario at the expense of –often prohibitively- high numerical complexity. Moreover, they are independent of the array geometry, in the sense that the same realization of the ray parameters can be used to generate the channel coefficients of any array geometry. This is very useful when comparing the performance of different geometries under a specific environment. The main disadvantage is that they are scenario dependent and have therefore little use in modelling other, even similar, propagation environments. Moreover, it is often difficult, if not impossible, to extract the statistics of the parameters from the measurements.

In MEMBRANE, one of the most crucial objectives is interference management. To this end, multi-user techniques such as beamforming play a vital role. Based on the above, directional channel modelling is chosen as the basic framework for channel modelling. Furthermore, this decision is encouraged by the fact that the main source of information regarding spatiotemporal channel modelling for relay-based deployments is the IST WINNER project [WIN D54], which has adopted the same modelling approach.

Last but not least, when developing a channel model a typical distinction between link-level and system-level models has been made, in the sense that the former is focused on reflecting the parameters affecting a single link performance whereas the latter is further concerned with the representation of parameters associated with the multiple-link, multiple-access point performance evaluation. As pointed out in [WIN D54] this distinction although is mostly convenient in that it simplifies modelling and decouples certain parameters, it may lead to inaccurate conclusions, as certain parameters impact at the link level does not necessarily translate to similar behaviour at the system level, where inter-sector parameter correlations need to be taken into account.

2.2.2 Directional channel modelling

Since the directional channel modelling is mainly used in MEMBRANE, the objective of this section is to detail the description of this approach. To this end, the link between a transmitting and a receiving array of $N^{(Tx)}$ and $N^{(Rx)}$ elements, respectively, is considered. The received complex signal vector $\underline{x}\left(t\right)\in C^{N^{(Rx)}\times 1}$ is expressed as

$$\underline{x}(t)=\sum_{j=1}^{L}\underline{S}_j^{(Rx)}\beta_j\exp\left(2\pi f_j t\right)\left(\underline{S}_j^{(Tx)}\right)^H\underline{s}\left(t-\tau_j\right)\qquad\in C^{N^{(Rx)}\times 1}\tag{2.1}$$

where $\underline{s}\left(t\right)\in C^{N^{(Tx)}\times 1}$ is the transmitted complex signal vector, L is the total number of rays, f_j models the doppler shift corresponding to the jth ray, and β_j, τ_j are the associated complex attenuation coefficient and delay, respectively. In equation (2.1) $\underline{S}_j^{(Rx)}$ [$\underline{S}_j^{(Tx)}$] is the receiving [transmitting] *array manifold vector* or *array response vector* of the jth ray, which depends on the array geometry and the DoA $\left(\theta_j^{(Tx)},\phi_j^{(Tx)}\right)$ [DoD $\left(\theta_j^{(Rx)},\phi_j^{(Rx)}\right)$] of this ray. From now on, β_j , τ_j ,$\left(\theta_j^{(Tx)},\phi_j^{(Tx)}\right)$,$\left(\theta_j^{(Rx)},\phi_j^{(Rx)}\right)$ and f_j will be collectively called as *ray parameter,* where $\left(\theta_j^{(Tx)},\phi_j^{(Tx)}\right)$ denotes the azimuth and elevation angles at the transmitter and $\left(\theta_j^{(Rx)},\phi_j^{(Rx)}\right)$ denotes the azimuth and elevation angles at the receiver. Assuming planar wave propagation, the array response vector is expressed as [Man04]:

$$\underline{S}_j = \underline{g}(\theta_j,\phi_j) \bullet \exp\left[\frac{-j2\pi f_c}{c} \underline{\underline{r}}^T \underline{u}(\theta_j,\phi_j)\right] \in C^{N\times 1} \tag{2.2}$$

where '$\bullet$' denotes the Hadamard element-wise multiplication, and we have omitted the superscript that denotes either the transmitting or the receiving array. In Eq. (2.2) f_c is the carrier frequency, c is the speed of light, $\underline{g}\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right)$ is the vector containing the complex responses (amplitude gain and phase) of the associated antenna elements at the specified direction, $\underline{\underline{r}}$ is the array geometry matrix and $\underline{u}\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right)$ is the unitary vector in the $\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right)$ direction. It is stressed that the array geometry and the direction $\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right)$ are defined with respect to the array Cartesian coordinate system that can be chosen arbitrary. It is:

$$\underline{g}\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right) = \left[g_1\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right) \quad \cdots \quad g_N\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right)\right]^{\mathrm{T}}$$

$$\underline{u}\left(\theta_{\mathrm{j}},\phi_{\mathrm{j}}\right) = \left[\cos\phi_{\mathrm{j}}\cos\theta_{\mathrm{j}} \quad \cos\phi_{\mathrm{j}}\sin\theta_{\mathrm{j}} \quad \sin\phi_{\mathrm{j}}\right]^{\mathrm{T}}$$

$$\underline{\underline{r}} = \left[\underline{r}_1 \quad \cdots \quad \underline{r}_N\right]$$

where the vectors $\underline{r}_1,\ldots,\underline{r}_N$ contain the antenna positions in Cartesian coordinates.

Having set the ground, the aim of the stochastic directional channel modelling now becomes more obvious; that is to determine the joint pdf of the ray parameters via statistical analysis of the measurement data. This task is mathematically intractable; therefore some simplifications are frequently applied with regards to the ray parameters inter-dependencies. For example, under a complex NLOS environment, where each ray arrives at the indoor station after several reflections, delay, DoA and DoD can be considered independent. It is also noted that very often elevation is not modelled in channel models, i.e. φ_{j} is assumed to be zero for all rays. Furthermore, it is important to stress that in general, all ray parameters are varying in time. However, these variations are considered large-scale effects and these parameters are assumed to be constant in the microscale. Though, time fading is caused due to the doppler effect.

Eq. (2.2) can be written in a compact form as:

$$x(\mathrm{t}) = \underline{\underline{\mathrm{H}}}\underline{s}'(\mathrm{t}) \tag{2.3}$$

where

$$\underline{\underline{\mathrm{H}}} = \left[\underline{S}_1^{(\mathrm{Rx})}\beta_1\left(\underline{S}_1^{(\mathrm{Tx})}\right)^{\mathrm{H}} \quad \cdots \quad \underline{S}_{\mathrm{L}}^{(\mathrm{Rx})}\beta_{\mathrm{L}}\left(\underline{S}_{\mathrm{L}}^{(\mathrm{Tx})}\right)^{\mathrm{H}}\right]$$

$$\underline{s}'(\mathrm{t}) = \begin{bmatrix} \underline{s}(\mathrm{t}-\tau_1) \\ \vdots \\ \underline{s}(\mathrm{t}-\tau_{\mathrm{L}}) \end{bmatrix}$$

One important aspect of the physical propagation process is *clustering*. That is, rays tend to appear in groups of similar delay, DoD and DoA. This phenomenon is attributed to the fact that multiple rays are reflected by each scatterer. The effects of clustering are significant. Clustering is responsible for the amplitude fading of the individual paths. As the number of rays in a cluster increases, the well-known Rayleigh distribution is approached. Furthermore, clustering affects the spatial characteristics of the channel by causing rapid fluctuations of the spatial correlation with the antenna element separation [Zha04]. To model clustering, Eq. (2.1) can be expressed in the form:

$$\underline{x}(\mathrm{t}) = \sum_{\mathrm{k=1}}^{\mathrm{K}} B_{\mathrm{k}} \exp\left(2\pi f_{\mathrm{k}} \mathrm{t}\right) \sum_{\mathrm{l=1}}^{\mathrm{L_k}} \underline{S}_{\mathrm{kl}}^{(\mathrm{Rx})}\left(\Theta_{\mathrm{k}}^{(\mathrm{Rx})} + \theta_{\mathrm{kl}}^{(\mathrm{Rx})}\right) \beta_{\mathrm{kl}} \left(\underline{S}_{\mathrm{kl}}^{(\mathrm{Tx})}\left(\Theta_{\mathrm{k}}^{(\mathrm{Tx})} + \theta_{\mathrm{kl}}^{(\mathrm{Tx})}\right)\right)^{\mathrm{H}} \underline{s}\left(\mathrm{t} - T_{\mathrm{k}} - \tau_{\mathrm{kl}}\right) \qquad (2.4)$$

where it has been implicitly assumed that all rays arrive/ depart with zero elevation. This is a common practice in channel modelling since the antenna array configurations that are commonly used are not selective in elevation. In Eq. (2.4), K is the number of clusters and $\mathrm{L_k}$ is the number of rays belonging to the $\mathrm{k^{th}}$ cluster. Moreover, two classes of parameters are defined, namely the *inter-cluster* and the *intra-cluster* parameters. The former class is composed by B_{k}, T_{k}, $\Theta_{\mathrm{k}}^{(\mathrm{Rx})}$ and $\Theta_{\mathrm{k}}^{(\mathrm{Tx})}$, which are the complex amplitude, the ToA, the Azimuth-of-Arrival (AoA) and Azimuth-of-Departure (AoD) of the k^{th} cluster. They are defined as the amplitude corresponding to the total power of all rays within that cluster, the ToA of the first arriving ray, the mean AoA and mean AoD, respectively. The intra-cluster parameters class is composed by β_{kl}, τ_{kl}, $\theta_{\mathrm{kl}}^{(\mathrm{Rx})}$ and $\theta_{\mathrm{kl}}^{(\mathrm{Tx})}$, which are defined as the amplitude, excess ToA, offset AoA and offset AoD of the l^{th} MPC in the k^{th} cluster relative to B_{k}, T_{k}, $\Theta_{\mathrm{k}}^{(\mathrm{Rx})}$ and $\Theta_{\mathrm{k}}^{(\mathrm{Tx})}$, respectively.

2.3 Proposed Channel Models

Spatiotemporal channel modelling for the relay-based infrastructure has attracted much interest lately. Currently, only few measurement reports can be found in the literature, which are useful when modelling individual aspects of the channel. In [WIN D54] one can find a literature review in channels models that are suitable for the MEMBRANE propagation scenarios. Based on that, the authors derive some useful channel models. In the same document channel models that concern some other scenarios are reported as well. Although these scenarios have some differences from the MEMBRANE propagation scenarios, they can be used for initial simulations after some essential modifications.

2.3.1 Antenna gain patterns

For omni-directional antenna elements, the antenna gain should be 0 dBi for every DoA or DoD. For 3-sector or 6-sector antennas, the pattern proposed in [3GPP SCM]can be used:

$$g\left(\theta\right) = -\min\left[12\left(\frac{\theta}{\theta_{3\mathrm{dB}}}\right)^2, g_m\right]\mathrm{dBi} \qquad (2.5)$$

where θ is defined as the azimuth between the direction of interest and the boresight of the antenna and $\theta_{3\mathrm{dB}}$ is the 3 dB beamwidth that is equal to 70° and 35° for a 3-sector and 6-sector configuration, respectively. Moreover, g_m is the maximum attenuation that is equal to 20 dB and 23 dB for a 3-sector and 6-sector configuration, respectively.

Particularly for the case of the channel models provided in sections 2.3.2 and 2.3.3, a restriction is that for distances larger than 300 m the 3 dB beamwidth of one of the link ends should be smaller than 10 degrees while the other should be smaller than 53 degrees.

2.3.2 Propagation scenario U1: Rooftop to rooftop

2.3.2.1 Large-scale effects

In [WIN D54], for path-loss the following formula is proposed:

$$\mathrm{L} = 36.5 + 20\log(\mathrm{f_C}/2.5\mathrm{GHz}) + 23.5\log(\mathrm{d}) \qquad (2.6)$$

For shadowing, a lognormal distribution with 3.4 dB standard deviation can be used.

2.3.2.2 Small-scale effects

In [WIN D54], a “clustered delay line” (CDL) model is provided. Basically, this model is based on the principles of the directional channel modelling with clustering. Nevertheless, some simplifications have been applied. For instance, intra-cluster delay spread is not modelled or in other words, all rays within a cluster are assumed to be arriving at exactly the same time.

The model provided is of reduced variability, i.e. most multipath component parameters are kept fixed. The channel characteristics were chosen as shown in Table 2.3. It is explicitly stressed that this selection was done based on a literature review. However, the authors believe that this model can provide representative results and that it could be used as a starting point in simulations.

Table 2.3 – Rooftop to rooftop channel model desired properties

Property	**Value**
Power delay profile	exponential (non-direct paths)
delay spread	40 ns
K-factor	10 dB
XPR	30 dB
Doppler	A peak centred around zero with most energy within 0.1 Hz
Angle spread of non-direct components	Gaussian distributed clusters with 0.5 degrees intra-cluster angle spread. Composite angle spread is 2 degrees. Same in both ends.

Based on the above results, the multipath component parameters are derived in Table 2.4. In total 10 clusters are defined, from which the first is the direct one. Non-direct clusters are composed of 10 rays, while the direct one contains an additional ray. The total power is normalized to 0 dB. The ray offset angles are the same for all clusters and they are given in Table 2.5. These values have been chosen in such a way so as to approach a Laplacian intra-cluster Power Angle Spectrum (PAS) with the desired intra-cluster angle spread.

Table 2.4 –CDL model for the rooftop to rooftop LOS case

<table>
<tr><th>cluster #</th><th>delay [ns]</th><th>total power [dB]</th><th>mean AoD (^{o})</th><th>mean AoA (^{o})</th><th>scatterer doppler frequency [mHz]</th><th>number of rays</th><th colspan="2">ray power [dB]</th></tr>
<tr><td>1</td><td>0</td><td>-0.39</td><td>0.0</td><td>0.0</td><td>41.6</td><td>1+10</td><td>-0.42</td><td>-32.2</td></tr>
<tr><td>2</td><td>10</td><td>-20.6</td><td>0.9</td><td>0.2</td><td>-21.5</td><td rowspan="7">10</td><td colspan="2">-30.6</td></tr>
<tr><td>3</td><td>20</td><td>-26.8</td><td>0.3</td><td>1.5</td><td>-65.2</td><td colspan="2">-36.8</td></tr>
<tr><td>4</td><td>50</td><td>-24.2</td><td>-0.3</td><td>2.0</td><td>76.2</td><td colspan="2">-34.2</td></tr>
<tr><td>5</td><td>90</td><td>-15.3</td><td>3.9</td><td>0.0</td><td>10.5</td><td colspan="2">-25.3</td></tr>
<tr><td>6</td><td>95</td><td>-20.5</td><td>-0.8</td><td>3.6</td><td>-20.2</td><td colspan="2">-30.5</td></tr>
<tr><td>7</td><td>100</td><td>-28.0</td><td>4.2</td><td>-0.7</td><td>1.3</td><td colspan="2">-38.0</td></tr>
<tr><td>8</td><td>180</td><td>-18.8</td><td>-1.0</td><td>4.0</td><td>2.2</td><td colspan="2">-28.8</td></tr>
</table>

9	205	-21.6	5.5	-2.0	-15.4		-31.6
10	260	-19.9	7.6	-4.1	48.9		-29.9

Table 2.5 – Ray offset angles

Ray number	Basis vector offset angles (BO)	Ray offset angles (OA)
1,2	± 0.0742	OA = intra-cluster angle (azimuth) spread x BO
3,4	± 0.2532	
5,6	± 0.4986	
7,8	± 0.8913	
9,10	± 1.9718	

2.3.3 Propagation scenario U2 – LOS: Below-rooftop to below-rooftop LOS case

2.3.3.1 Large-scale effects

The classical two ray model with ground reflection results in the so-called breakpoint distance located at a distance r_b given by

$$r_b = 4\frac{h_b h_m}{\lambda} \tag{2.7}$$

where h_b, h_m are the heights of the two ends of the link and λ is the wave length. When the distance between the two ends is smaller than r_b, almost free-space propagation is experienced. After that point, the path-loss slope is increased. In practice, various measurements have revealed that the actual breakpoint distance changes due to reflection from cars and other objects and that it is given by

$$r_b = 4\frac{(h_b - h_o)(h_m - h_o)}{\lambda} \tag{2.8}$$

where h_o is an effective ground height which is typically in the range 1.2-1.6 m. Therefore, we need 4 to 4.5 meter high antennas to achieve a 500 m free-space propagation. Based on this parameter, the proposed path-loss formula is defined as

$$\begin{aligned} \mathrm{L} &= -20\log(\lambda/4\pi r), r \le r_\mathrm{b} \\ \mathrm{L} &= -20\log(\lambda/4\pi r_b) + 40\log(r/r_\mathrm{b}), r > r_\mathrm{b} \end{aligned} \tag{2.9}$$

For shadow fading, a lognormal distribution with a standard deviation of 3 dB and 7 dB for the case where the distance r is less or more than the breakpoint distance, respectively, is proposed.

2.3.3.2 Small-scale effects

Similarly, a CDL model is given in [WIN_D5.4] for the case of below-rooftop to below-rooftop propagation. Three cases are distinguished depending on the path-loss value as indicated in Table 2.6.

Table 2.6 – Below-rooftop to below-rooftop channel model desired properties

Figure	Value
Power delay profile	exponential (non-direct paths)
Range definition	Range 1: $L<85$ Range 2: $85<L<110$ Range 3: $L>110$
delay spread	Range 1: 30 ns Range 2: 110 ns Range 3: 380 ns
K-factor	Range 1: 10 dB Range 2: 2 dB Range 3: 1 dB
XPR	9 dB
Doppler	A peak centred around zero with most energy within a few Hz
Angle spread of non-direct components	uniformly distributed clusters at [0,360) with 2 degrees intra-cluster angle spread

Based on the above, the multipath component parameters are derived in Table 2.7.

Table 2.7 – CDL model for the below-rooftop to below-rooftop, range 1 case

cluster #	delay [ns]	total power [dB]	mean AoD $(^o)$	mean AoA $(^o)$	scatterer doppler frequency [mHz]	number of rays	ray power [dB]	
1	0	-0.37	0.0	0.0	744	1+10	-0.41	-30.1
2	5	-15.9	-71.7	70.0	-5	10	-25.9	
3	15	-22.2	167.4	-27.5	-2872		-32.2	
4	20	-24.9	-143.2	106.4	434		-34.9	
5	40	-26.6	34.6	94.8	295		-36.6	
6	45	-26.2	-11.2	-94.0	118		-36.2	
7	50	-22.3	78.2	48.6	2576		-32.3	
8	70	-22.3	129.2	-96.60	400		-32.3	
9	105	-29.5	-113.2	41.7	71		-39.5	
10	105	-17.7	-13.5	-83.3	3069		-27.7	
11	125	-29.6	145.2	176.8	1153		-39.6	
12	135	-26.6	-172.0	93.7	-772		-36.6	
13	140	-23.4	93.7	-6.4	1298		-33.4	

14	240	-30.3	106.5	160.3	-343		-40.3
15	300	-27.7	-67.0	-50.1	-7		-37.7
16	345	-34.8	-95.1	-149.6	-186		-44.8
17	430	-38.5	-2.0	161.5	-2287		-48.5
18	440	-38.6	66.7	68.7	26		-48.6
19	465	-33.7	160.1	41.6	-1342		-43.7
20	625	-35.2	-21.8	142.2	-61		-45.2

2.3.4 Propagation scenarios U2 – NLOS: Below-rooftop to below-rooftop, and U3: rooftop to below-rooftop

For the propagation scenarios U2 – NLOS and U3 – LOS/NLOS, [WIN D54] does not consider any equivalent scenarios. Nevertheless, for initial simulation purposes, some solutions are proposed here.

- For U2-NLOS, the channel model corresponding to scenario B1 of the WINNER project could be used after some modifications. This scenario concerns the case of the urban environment, in which the mobile station (MS) is low-lying at 1.5 meters above the ground level and the BS is at some moderate height but still below rooftop level. Scenario B1 has been fully developed (it is not of reduced variability) based on measurements conducted within the framework of the same project. A detailed description of the implementation is given in [WIN D54]. This model is asymmetric in the sense that it assumes a larger angle spread in the MS side than in the BS side. Some modifications that need to be considered, are:
    - **Delay spread and angle spread.** By lifting up the MS, the scattering environment becomes less dense and it is expected that both angle spread at that side and delay spread will be increased. This can be taken into account in a straightforward manner by re-setting the values of the corresponding parameters.
    - **The path-loss formula.** It is well known that path-loss is sensitive to the mobile height in NLOS conditions. Therefore, since the MS is switched to a moderate-height node, a model that accounts for that should be used.
    - **Doppler effect.** As stated previously, in MEMBRANE nodes are fixed and Doppler fading is caused only due to the motion of scatters. The Doppler spectrum is expected to have a peak at zero with most energy concentrated within a few Hz.
- For U3-NLOS, the 3GPP/3GPP2 SCM model [SCM] or its extended SCME “urban microcell” model [SCME] could be used as a basis. Similarly, this scenario considers the case where the mobile station (MS) is low-lying at 1.5 meters above the ground level and the BS is at rooftop level. Similarly, the delay spread, angle spread, path-loss formula and Doppler model should be altered.

2.3.5 Propagation scenarios R1: planned infrastructure and R2: non-planned links

As stated before, mobile height is less critical in the rural LOS or NLOS environment. In that sense, for scenario R2, the SCM model (and its extended SCME suburban macrocellular channel model) or the WINNER D1 Rural macrocell model can be used to perform link-level and system-level simulations. These models have been fully developed (it is not of reduced variability) based on measurements. A detailed description of the implementation is given in [SCM], [SCME], and [WIN D54]. However, for simulations considering Doppler fading, it is essential that some modifications are performed. The Doppler spectrum is expected to have a peak a zero with most energy concentrated within a few Hz. Note that this SCME model is originally proposed for suburban area while the WINNER D1 model has low height of 1.5 m at MS.

For scenario R1, channel models are not available at the literature. Nevertheless, modelling this propagation scenario is relatively easy. A very small angle spread, in the order of 1 degree is expected in both ends. Delay spread is also very small with its actual value being dependent on the link distance. A channel model that accounts for this propagation scenario will be developed within the context of MEMBRANE based on a literature review of measurements reports. For instance, a two-ray model might be used as a good starting point for the pathloss model in R1 scenarios.

Table 2.8 – CDL model for the below-rooftop to below-rooftop, range 2 case

cluster #	delay [ns]	total power [dB]	mean AoD (^{o})	mean AoA (^{o})	scatterer doppler frequency [mHz]	number of rays	ray power [dB]	
1	0	-1.5	0.0	0.0	744	1+10	-1.8	-24.7
2	5	-10.2	-71.7	70.0	-5	10	-20.2	
3	30	-16.6	167.4	-27.5	-2872		-26.6	
4	45	-19.2	-143.2	106.4	434		-29.2	
5	75	-20.9	34.6	94.8	295		-30.9	
6	90	-20.6	-11.2	-94.0	118		-30.6	
7	105	-16.6	78.2	48.6	2576		-26.6	
8	140	-16.6	129.2	-96.60	400		-26.6	
9	210	-23.9	-113.2	41.7	71		-33.9	
10	210	-12.0	-13.5	-83.3	3069		-22.0	
11	250	-23.9	145.2	176.8	1153		-33.9	
12	270	-21.0	-172.0	93.7	-772		-31.0	
13	275	-17.7	93.7	-6.4	1298		-27.7	
14	475	-24.6	106.5	160.3	-343		-34.6	
15	595	-22.0	-67.0	-50.1	-7		-32.0	
16	690	-29.2	-95.1	-149.6	-186		-39.2	
17	855	-32.9	-2.0	161.5	-2287		-42.9	
18	880	-32.9	66.7	68.7	26		-42.9	
19	935	-28.0	160.1	41.6	-1342		-38.0	
20	1245	-29.6	-21.8	142.2	-61		-39.6	

Table 2.9 – CDL model for the below-rooftop to below-rooftop, range 3 case

cluster #	delay [ns]	total power [dB]	mean AoD (°)	mean AoA (°)	scatterer doppler frequency [mHz]	number of rays	ray power [dB]	
1	0	-2.6	0.0	0.0	744	1+10	-3.0	-23.0
2	10	-8.5	-71.7	70.0	-5	10	-18.5	
3	90	-14.8	167.4	-27.5	-2872		-24.8	
4	135	-17.5	-143.2	106.4	434		-27.5	
5	230	-19.2	34.6	94.8	295		-29.2	
6	275	-18.8	-11.2	-94.0	118		-28.8	
7	310	-14.9	78.2	48.6	2576		-24.9	
8	420	-14.9	129.2	-96.60	400		-24.9	
9	630	-22.1	-113.2	41.7	71		-32.1	
10	635	-10.3	-13.5	-83.3	3069		-20.3	
11	745	-22.2	145.2	176.8	1153		-32.2	
12	815	-19.2	-172.0	93.7	-772		-29.2	
13	830	-16.0	93.7	-6.4	1298		-26.0	
14	1430	-22.9	106.5	160.3	-343		-32.9	
15	1790	-20.3	-67.0	-50.1	-7		-30.3	
16	2075	-27.4	-95.1	-149.6	-186		-37.4	
17	2570	-31.1	-2.0	161.5	-2287		-31.1	
18	2635	-31.2	66.7	68.7	26		-31.2	
19	2800	-26.3	160.1	41.6	-1342		-36.3	
20	3740	-27.8	-21.8	142.2	-61		-37.8	

3 INTERFERENCE MODELLING

Interference is a critical issue in the context of MEMRANE, since it affects the maximum attainable performance in terms of bit error rate (BER) and achievable data rate of a certain MIMO link. Furthermore it is a reconfiguration parameter, according to which robust transceivers are to be designed. In a MEMRANE scenario, the number and propagation characteristics of strong interferers may vary, as a result of fading caused by moving scatterers and the scheduling and routing decision strategies deployed. Moreover, adequate interference modelling is critical, as scheduling, routing and power control decisions may rely on interference characteristics.

Interference modelling is mainly a function of propagation characteristics, MIMO channel modelling and the system deployment assumptions and dynamics. In order to capture the dynamics of both the propagation and system deployment aspects in an accurate interference model, computational complexity usually becomes a prohibitive factor.

3.1 Link level interference modelling

A simplification of interference modelling for the *link level studies* is often pursued in order to overcome the computational complexity issues.

The simplest model for interference is the additive white Gaussian noise (AWGN). This is sufficient in order to assess the transceiver performance as a function of the desirable channel characteristics and slow fading interference.

In order to reflect the impact of channel fading and dynamics, implementation of the interfering channels using the same model as for the desirable channel is required. A common simplification in this case is to introduce at the link level only a small number of interferers –as the stronger ones- and abstract the remaining interferers by their ‘equivalent’ AWGN component. This is equivalent to taking into account a number of interference ‘rings’ around the cell of interest in a typical cellular set up.

In the early stage of MEMBRANE Project, perfect synchronisation may be assumed for different nodes in the network and some efficient algorithms can be developed to combat the interference. Later on, apart from the spatial model for interference, it is also important to model interference in time in the case when interfering and desired signal are asynchronous. The interference appears in an instant randomly chosen between the start of desired user transmission and its end. If the structure of the interference is not relevant for the algorithm performance, it can be simulated as spatially-coloured temporally-white Gaussian noise. If the structure of interference is relevant (e.g. active interference cancellation techniques), then explicit representation of the interfering signal is necessary.

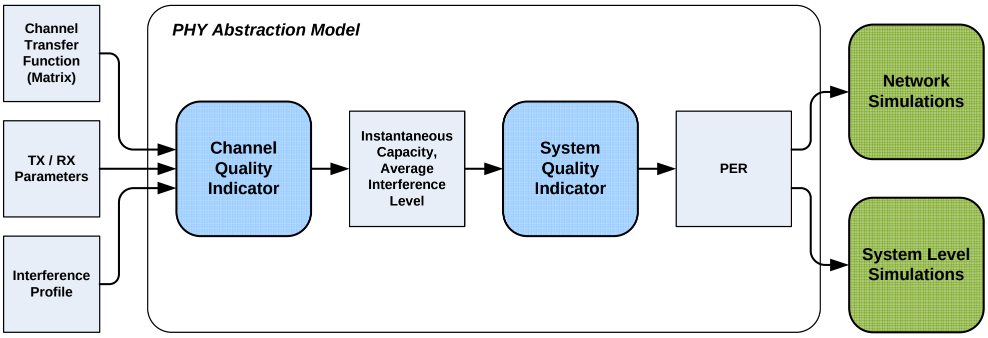

Figure 3.1 – Block diagram of the Physical Layer abstraction model

3.2 System level methodology

As pointed out in [Pep05], [Bru05], striking the right balance on the trade-off between complexity and accuracy is the main challenge of system level evaluation, in a broadband, multi-antenna deployment with large number of resource elements to be managed (e.g. subcarriers, spatial channels) and the implementation of fast scheduling, fast link adaptation in form of fast power control and adaptive modulation and coding, or other advanced schemes such as Hybrid Automatic Repeat Request (HARQ) to be performed.

Traditionally, the performance of the radio links has been evaluated in terms of the packet error rate (PER) as a function of signal-to-interference plus noise ratio (SINR), averaged over all channel realizations of one specific channel model. PER versus average SINR performance has therefore been used as the interface between the link- and system-level simulators. This may be adequate as long as every transmitted packet encounters similar channel statistics, which implies very large packet sizes/coding blocks with respect to the channel coherence time. But in case of data-centric radio networks, this condition is generally not fulfilled. Consequently, assessing the performance of fast resource scheduling and fast link adaptation in system level simulations requires a more accurate link quality model accounting for the instantaneous channel conditions.

Modelling approaches taking account the instantaneous channel and interference characteristics have been proposed in the literature (see [Pep05], [Bru05] and reference therein). Once the scheduler has determined what resources are allocated to which users at what power level, the individual effective (MIMO) channels including pathloss, shadowing, small- (and large) scale fading as well as intercell interference are computed.

Since different bits can be transmitted on different spatial layers, in different OFDM (Orthogonal Frequency Division Multiplexing) symbols, and on different OFDM subcarriers they may have different quality. Thus, we have a *multi-state channel*. The total number of resource elements in frequency, time and space is typically by far too large for direct use of the associated quality measures (such as SINR) in the mapping to PER. The set of quality measures needs therefore to be *compressed* to a much smaller set of typically only 1 or 2 scalar indicators. The selection of a suitable compression function, i.e. a **link-to-system interface metric** or **physical layer abstraction model,** is crucial for the accuracy of the system level evaluation.

MIMO capacity for Gaussian signalling was shown to provide an adequate link-to-system interface metric in [Pep05]. It was shown that under the assumption of additive white Gaussian noise and unstructured interference the metric provides a good interface. However, in the presence of structured interference and for small number of strong interferers the metric cannot provide a suitable interface due to considerable deviation from the Gaussian assumption that is made for noise plus interference. For large number (>2) of interferers the Gaussian assumption becomes more and more accurate and the channel capacity metric can provide a suitable interface. Note that the channel capacity considered here inherently provides already a sum across spatial modes, rendering the assessment of different receiver options impossible. Furthermore, a capacity metric will most likely work well for systems that exploit a large amount of the capacity (e.g., for open-loop capacity and adaptive matrix modulation or closed-loop MIMO capacity and SVD-based MIMO), but might be less appropriate, if an adaptation of the transmission mode is not applied.

In order to obtain a quality model of reduced complexity and training effort, a one-dimensional mapping between a so-called effective SINR and the PER has been considered in [Bru05]. The compression function is of the form:

$$\mathrm{SINR}_{\mathrm{eff}} = \alpha_1 I^{-1}\left(\frac{1}{P}\sum_{p=1}^{P} I\left(\frac{1}{\alpha_2}\mathrm{SINR}_p\right)\right) \tag{3.1}$$

where α_1 and α_2 are model parameters and the $\mathrm{SINR}_{\mathrm{eff}}$ corresponds to the parameters resulting from the compression and SINR_p are the set of parameters to be compressed.

Four potential candidates for the selection of function *I*() have been considered:

- capacity effective SINR metric (CESM)
- exponential effective SINR metric (EESM)
- mutual information effective SINR metric (MIESM) and
- logarithmic effective SINR metric (LESM)

The complexity of the proposed model may be challenging, depending on the space-time processing and the propagation and system deployment, and decimation in time and frequency need to be considered. Note that in the MEMBRANE Project, the instantaneous capacity based compression function is considered as the preferable approach.

3.3 Wireless multihop backhaul specifics

When identifying the interference modelling for the link and system level studies in MEMBRANE, it is important to consider that interference in the backhaul multihop network can by classified in 2 types:

(a) self-interference that prevents a single access point from simultaneously transmitting and receiving, or from simultaneously receiving from multiple neighbours on the same subchannel;

(b) cross-link interference, caused by transmissions using the same subchannel over two separate links with distinct receivers that are located close to each other.

Access traffic from the users to their respective access points is typically assumed to be transmitted in a separate frequency band and does not interfere with the wireless backhaul traffic. Separate links in the backhaul may interfere with each other, depending on the locations of their receiving end points and the antenna technology used for transmission and reception. Such pairs of directed links that cannot be simultaneously active in the backhaul network can be precomputed. Therefore, we can, in principle, assume that interfering link pairs are specified as input.

SDMA in MEMBRANE will allow nodes to have simultaneous reception or transmission of multiple packets. A spatial scheduling scheme will complement the SDMA transceiver based on a measure of ‘separability’ between nodes, which is a function of parameters such as angle, correlation and SINR.

3.4 Example deployment for interference modelling

As depicted in Figure 3.2, a ‘regular’ network topology with hexagonal cells is plotted [Vis06]. The AN is located in the centre of the cell, and is surrounded by INs in three rings. We assume in the multi-hop network, only the nodes in adjacent rings can communicate with each other. One way to simplify interference modeling is to assume the interference comes from the stongest interferers located in the first adjacent ring that talk simultaneously. Other deployment scenarios accounting for sectored operation of nodes and various frequency reuse schemes across sectors will also be considered. These scenarios will be used to model interference environment in multi-hop network having nodes with switched beam or adaptive beam antennas.”

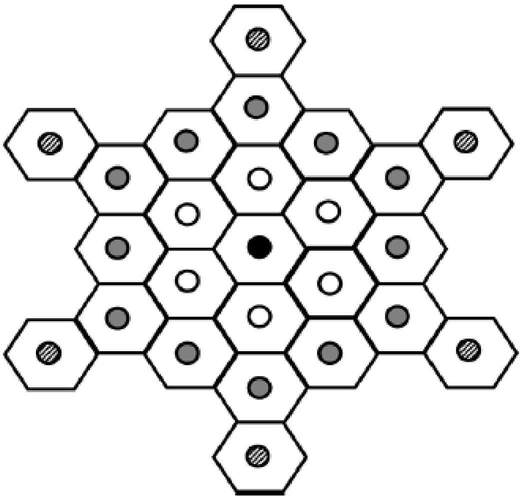

Figure 3.2 – A ‘regular’ network topology with hexagonal cells

4 PHYSICAL LAYER PARAMETERS & PERFORMANCE METRICS

4.1 Basic PHY assumptions

Table 4.1 – System parameters

Parameter	Value
Centre frequency	2.5 GHz/3.5 GHz/5.0 GHz
Bandwidth	100 MHz (scalable to 10 MHz)
Duplex scheme	TDD/FDD
Average transmit power	20dbm – 40dbm
FEC	Convolutional code ($133_8, 171_8$) / convolutional turbo code/ concatenated code
code rates	1/2, 2/3, 3/4
interleaver	Space-Frequency interleaver
modulation alphabet	BPSK, QPSK, 16QAM, 64QAM
multiple access	OFDMA/SDMA
Number of sectors	Omni /3/6 sector(s)
Antenna configuration	ULA / UCA (optional), 1/2/4/8 antennas (optional), 0.5λ / 4λ
channel estimation	Pilot-aided channel estimation (8 pilot subcarriers out of 256)
synchronisation	Assume as perfect
CSI quality	Full CSI at the receiver, full/partial/no CSI at the transmitter
(H)ARQ	No HARQ
Power control	No power control
Power requirements	External/Internal, 240V/110V,

Table 4.2 – Scenario parameters

Parameter	Value
Channel model	U1/U2/U3 (see Table 2.1– Propagation scenarios in the urban case), R1/R2 (see Table 2.2– Propagation scenarios in the rural case)
Path loss	Log-distance pathloss model, see Sec. 2.3 Proposed Channel Models
Shadow fading	Log-normal distribution, see Sec. 2.3 Proposed Channel Models
Node topology	Multi-hop topology with 19 nodes in a hexagonal deployment

Traffic model	Depends on applications (Constant / lognormal / exponential)
Interference model	In a hexagonal cell topology, the AN is surrounded by INs in 3 rings. Links can only be formed between adjacent rings. We assume the interference comes from the first ring of strong interferers
Cell size	5-10 km for rural area, 1-2 km for urban area

4.2 Performance metrics

Reconfigurable multiple antenna performance evaluations will primarily aim at assessing the gains over conventional approaches to be considered as *baseline*.

Initially, reconfigurable multiple antenna techniques optimising a single link will be investigated for a number of system parameters and scenarios of interest. Single communications link performance metrics will be considered in this case. For multiple antenna techniques optimising performance in the multi-link case by exploiting ‘multi-user diversity’, a simplified traffic model based on the full queue assumption without detailed modelling of packets will be adopted. Most investigations will be based on snapshots without short-term evolution of the individual and uncorrelated drops of large-scale parameters.

After establishing the performance gains of reconfigurable multiple antenna techniques in the single link and simplified multi-link set up, the system level performance will be assessed taking into account a realistic wireless backhaul node topology, traffic patterns and delay constraints.

The objective is to ultimately integrate the multiple antenna studies into the jointly optimised scheduling and routing framework of MEMBRANE.

4.2.1 Link level performance metrics

At the link level, the following performance metrics have been identified:

- BER, FER and PER as a function of the SINR for a certain achieved data rate.
- Single-link throughput averaged over the fading at some pre-determined FER or PER. This is the main metric of interest for packet-switched data, especially with link adaptation.
- Equivalent SNR degradation due to erroneous CSI feedback and imperfect channel estimation.

4.2.2 System level performance metrics

At the system level, studies will be focusing on the following performance metrics, further specified for the wireless backhaul problem:

- **Node throughput**: The node throughput is defined as the ratio of correctly received information bits to the total simulation time. Statistics are collected from all nodes within the evaluation area (e.g., hexagonal deployment). The cumulative distribution function (CDF) of the node throughput values or the average throughput can be used for evaluations. In a multihop environment *throughput versus range* can provide a metric of the efficiency of multiple hops as compared to the single hop case.
- **Node spectral efficiency**: The node spectral efficiency is given as the ratio of the node’s throughput to the frequency bandwidth occupied by the node. It describes how good the

multi-hop system operates in different frequency reuse scenarios, duplex schemes, etc. Average spectral efficiency across nodes and possibly CDF may be evaluated.

- **Link delay**: The delay introduced in a single link (EN-to-IN/IN-to-IN/IN-to-AN) is of critical importance in a wireless backhaul scenario. Cross layer designs that take into account QoS criteria and attempt to jointly optimise throughput and delay characteristics will be the subject of both multiple antenna and scheduling algorithm development. In that respect, *throughput versus delay* can provide a metric to jointly characterise performance and fairness.
- **End-to-end performance metric**: The end-to-end performance concerns the transmission from the AN to the EN. In wireless backhaul scenario considered in MEMBRANE Project, such a performance metric needs to assess the trade-off between the overall throughput and the end-to-end delay. A good performance metric will demonstrate a good trade-off which depends on applications.
- **Robustness**: Channel estimation errors at the receiver cause degradation in the decoding performance. Moreover, they affect the performance of closed-loop multiple antenna techniques, since the erroneous CSI is used as feedback for spatial processing. Additional errors result from quantisation and feedback delay. To assess robusteness, a simple (e.g. Gaussina) error model can be introduced into the channel estimates and the CSI feedback. The incurred performance loss as compared to the error free case is then a measure of robustness.
- **Control signalling overhead**: The evaluation of the associated control overhead of each technique is an important part of the investigations in that it allows the assessment of the trade-off of performance versus complexity. For each technique the required additional control information (e.g., spatial adaptation metric, CSI used for beamforming or linear precoding, etc.) should be estimated in terms of the number of required bits in the control channel.
- **Reconfigurability**: The ability of multi-antenna techniques to intelligently adapt and achieve optimal performance in the presence of parameter variations, such as propagation, traffic and network topology, is a measure of reconfigurability. It can be defined as a performance gain achieved (such as throughput, spectral efficiency, link delay) by exploiting adaptive algorithms in the presence of parameter variations. Performance gain can be measured as a result of comparison of three baseline antenna configurations in the system: fixed antenna patterns, switched beams and adaptive beamforming, through various algorithms. It should be noted that reconfigurability to varying reliability of CSI is crucial for the robustness of techniques that exploit CSI.

5 MULTIPLE ANTENNA TECHNIQUES FOR MEMBRANE

5.1 Benefits of multiple antenna processing

Multiple antenna systems can improve the link quality, by combating the effects of multipath propagation or constructively exploiting the different paths, and increase capacity by mitigating interference and allowing the transmission of different data stream from different antennas. More specifically the benefits of multiple antenna processing can be summarised as follows:

- Increased range/coverage: The array or beamforming gain is the average increase in signal power at the receiver due to a coherent combination of the signals received at all antenna elements. It is proportional to the number of receive antennas and also allows for lower battery life.
- Lower power requirements and/or cost reduction: By optimising transmission towards the wanted user (transmit beamforming gain) achieves lower power consumption and lower amplifier costs.
- Improved link quality/reliability: Diversity gain is obtained by receiving independent replicas of the signal through independent fading signal components. Based on the fact that it is highly probable that at least one or more of these signal components will not be in a deep fade, the availability of multiple independent dimensions reduces the effective fluctuations of the signal. Forms of diversity include temporal, frequency, code and spatial. The spatial diversity is obtained when sampling the spatial domain with multiple antennas. The maximum spatial diversity order of a non-frequency selective fading MIMO channel is equal to the product of the number of receive and transmit antennas. Transmit diversity with multiple transmit antennas can be exploited via special modulation and coding schemes [Pau03], whereas receive diversity relies on the combination of independent fading signal dimensions.
- Increased spectral efficiency: Precise control of the transmitted and received power and exploitation of the knowledge of training sequence and/or other properties of the received signal (e.g., constant envelope, finite alphabet, cyclostationarity) allows for interference reduction/mitigation and increased number of users sharing the same available resources (e.g., time, frequency, codes) and/or the reuse of these resources by users served by the same base station/access point. The latter introduces a new multiple access scheme, which exploits the space domain, the SDMA. Moreover increased data rates, and therefore increased spectral efficiency can be achieved by exploiting the spatial multiplexing gain, that is the possibility to simultaneously transmit multiple data streams exploiting the multiple independent dimensions, the so called spatial signatures or MIMO channel eigenmodes. It was shown in [Fos98] that in case of uncorrelated Rayleigh fading the MIMO channel capacity limit grows linearly with min(M, N), where M and N denote the number of transmit and receive antennas, respectively.

5.2 Multiple antenna transceiver architectures

In a MIMO antenna system as the one illustrated in Figure 5.1, the data block to be transmitted is encoded and modulated to symbols of a complex constellation. Each symbol is then mapped to one of the transmit antennas (spatial multiplexing) after space-time weighting of the antenna elements. After transmission through the wireless channel, demultiplexing, weighting, demodulation and decoding is performed at the receiver in order to recover the transmitted data.

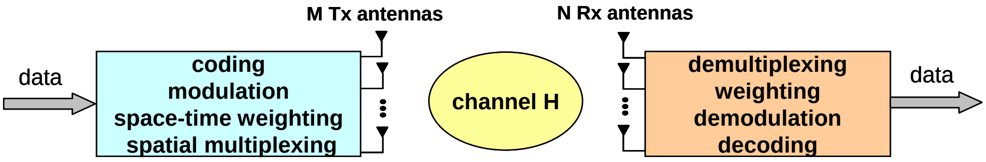

Figure 5.1 – Multiple antenna transceiver architecture

A large number of transmission schemes over MISO or MIMO channels have been proposed in the literature, designed to maximize spectral efficiency and link quality through the maximization of diversity, data rate and SINR. Each of these schemes relies on a certain amount of CSI available at the transmitter and/or at the receiver side. CSI at the transmitter can be made available through feedback or can be obtained based on estimation of the receive channel. CSI at the receiver can be obtained using training-based or blind techniques, which exploit other properties of the received signal, such as constant envelope and the finite alphabet.

Transmission schemes, which do not require CSI at the transmitter, exploit the spatial dimension either by introducing coding on the spatial domain or by employing spatial multiplexing gain. The former approach, the so-called space-time coding [Pau03], increases redundancy over space and time, as each antenna transmits a differently encoded fully redundant version of the same signal. The received signal is detected using a Maximum Likelihood (ML) decoder. Space-time codes were originally developed in the form of Space-Time Trellis Codes (STTC), which requires a multidimensional Viterbi algorithm for decoding at the receiver. These codes can provide diversity equal to the number of transmit antennas as well as coding gain depending on the complexity of the code without loss in bandwidth efficiency. Space-Time Block Codes (STBC) offer the same diversity as the STTC but do not provide coding gain. However, STBC are often the preferred solution against STTC, as their decoding only requires linear processing. STBC for two transmit antennas (proposed by Alamouti [Ala98]) has been adopted as part of third generation (3G) standards. Space-Time Coding techniques assume in principle perfect CSI at the receiver. Nevertheless, unitary and differential Space-Time Coding has been proposed [Hoc00], which does not required CSI at any side of the communication link.

Layered space-time architectures exploit the spatial multiplexing gain by sending independently encoded data streams, in diagonal layers as originally proposed in [Fos98] or in horizontal layers, the so called V-BLAST (Vertical Bell labs Layered Space-Time) scheme [Fos99]. The receiver must demultiplex the spatial channels in order to detect the transmitted symbols. Various techniques have been used for this purpose, such as Zero-Forcing (ZF), which uses simple matrix inversion but results are poor when the channel matrix is ill conditioned; Minimum Mean Square Error (MMSE), which is more robust in that sense but provides limited enhancement if knowledge of the noise/interference is not used; and Maximum Likelihood (ML), which is optimal in the sense that it compares all possible combinations of symbols but can be too complex, especially for high-order modulation.

Transmission schemes, which require perfect CSI at the transmitter, optimize SINR by focusing energy into the desired directions, minimizing energy towards all other directions and satisfying transmit power constraints. Beamforming allows spatial access to the radio channel by means of different approaches, considering either short terms properties (e.g., directional parameters) or long-term properties (e.g., second order statistics) of the radio channel.

In the majority of cases it is reasonable to assume that only partial CSI is available at the transmitter. Hybrid schemes, which combine Space-Time Coding and beamforming, have been proposed which introduce precoding to exploit the available CSI when optimizing a certain criterion (e.g., pairwise error probability). Robust transmit beamforming schemes have also been proposed, that take into account CSI estimation errors and optimize transmission in terms of a performance criterion, such as Signal-to-Noise Ratio (SNR) and mutual information ([Jon02] and references therein).

At the receiving end of a SIMO or MIMO communication link, the receiver or equalizer collects the multiple signals from different paths and reconstructs the transmitted signal [Pau03]. In the case of frequency non-selective SIMO channel the optimal receiver strategy is to perform Maximum Ratio Combining (MRC) and maximize the received SNR. For frequency-selective SIMO channels, a ML detector is an optimal receiver but it is non-linear with complexity increasing exponentially in the number of channel dimensions. Linear receivers can be used instead, which have lower complexity at the expense of lower performance. A Zero-Forcing (ZF) equalizer is designed to eliminate Inter-Symbol Interference (ISI) by employing channel inversion at the expense of noise enhancement. To overcome this drawback, the Minimum Mean Square Error (MMSE) receiver balances noise enhancement with ISI elimination. A sub-optimal non-linear scheme based on decision feedback (Decision Feedback Equalizer –DFE) can be used to improve the performance of a linear equalizer by using the feedback filter to remove the portion of ISI from the present symbol caused by the previously detected symbols. Both ML and linear equalizers can be extended to the MIMO channel case. A new problem associated with MIMO receivers is the presence of multi-stream interference (MSI), resulting from the multiple data streams interfering with each other. Non-linear successive cancellation equalizers, or V-BLAST equalizers as commonly known [Fos99], convert the MIMO channel into a set of parallel channels with increasing diversity at each successive stage but with error performance dominated by the weakest stream. This drawback is partly overcome by applying ordered successive cancellation, where the strongest stream is decoded first.

5.3 Multiple antenna considerations in MEMBRANE

The use of intelligent antennas in ad hoc networks has recently attracted a great amount of attention as a means to optimise power transmission/reception ([Ban06] and references therein). Two basic types of intelligent antennas are considered in this context: switched beams (fixed beams) and adaptive antenna arrays. A switched beam antenna generates multiple pre-defined fixed beam patterns and applies one at a time towards the direction of interest. It is the simplest technique essentially providing sectorisation with the capability of illuminating the selected sector according to, for instance, an SNR-related metric. An adaptive (steerable) antenna array can formulate the beam structure based on a certain optimisation criterion, such as maximising the array gain towards the signal of interest and suppressing interfering signals.

The transmit/receive power optimisation and interference suppression capabilities of intelligent antennas have encouraged the consideration of similar techniques in multihop networks that are in general interference limited. However, it was made evident that to be able to leverage on the prospective gains, appropriate higher layer protocols design is required. In that respect, MAC layer protocol design for directional antennas is currently being studied ([Ban06] and references therein). Performance improvements resulting from the use of narrow fixed beams and the consequent reduction of interference were shown in [Vis06] in a linear programming framework for scheduling and routing in a multihop wireless backhaul set up.

In MEMBRANE, optimisation of the multihop wireless backhaul network performance through the use of the multiple antennas is performed in terms of:

1. the single communication link performance by reconfiguring the multiple antenna transceiver for a fixed scheduling and routing decision;
2. the multi-link performance through joint (cross layer) optimisation of the reconfigurable multiple antenna transceiver and the scheduling strategy for a fixed routing decision, and
3. the MEMRANE wireless backhaul end-to-end performance through joint (cross layer) optimisation of the reconfigurable multiple antenna transceiver and the scheduling/routing protocol.

The first two aspects are the main focus of the initial part of the studies and are also addressed in this deliverable. The third aspect will be investigated in the following using the input of WP3 and WP4.2.

In the following sections basic spatial processing approaches for the *optimisation of a single link* are discussed, namely intelligent antennas, space-time coding, spatial multiplexing and interference cancellation. Performance optimisation focuses on the following objectives:

- Improve link quality;
- Increase range;
- Optimise transmission/reception power and reduce interference;
- Increase spectral efficiency;
- Achieve reconfigurability to varying conditions;

Novel reconfigurable designs will then be presented, which enhance the performance of the basic spatial processing techniques through the exploitation of

- Channel parameters (e.g. antenna correlation, Demmel condition);
- Channel State Information reliability (depending on feedback signalling and CSI variability);
- Network topology, resulting in varying interference both in terms of number of interferers and interfering channels.

5.4 Intelligent antennas

As mentioned in the previous section the basic deployment of intelligent antennas in a multihop backhaul network would consists of a set of predefined beams at each node. The selection of the beam to use out of the set aims to maximise the signal towards a certain direction/node. The beams are assumed to have narrow main lobe and small side-lobes.

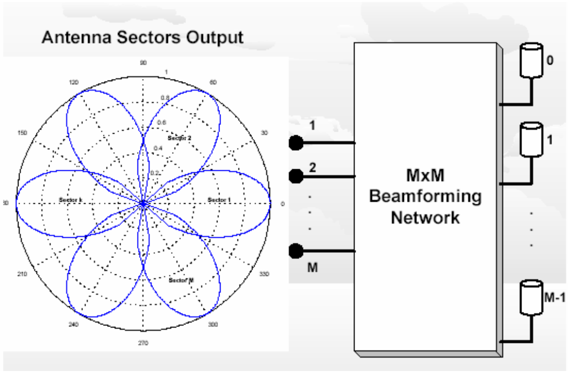

Figure 5.2 – Switched beam system

Adaptive beam systems consist of several antenna elements (array) whose signals are processed adaptively by a combining network, the signals received/transmitted from different antenna elements are multiplied with complex weights and then summed to create a steerable radiation pattern. The main lobe of the array pattern is steered towards the direction of desirable node and nulls can be placed in the direction of the interfering nodes. Adaptive beam systems have the ability to change the antenna array pattern dynamically to adjust to noise, interference, and multipath and to provide substantial gains (of the order of 10log(M) dB, where M is number of array elements) as compared to the omni directional antenna system.

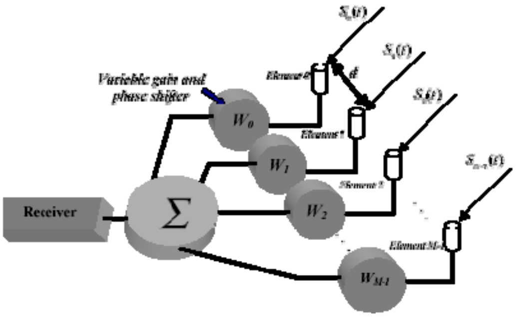

Figure 5.3 – Adaptive beam system

Switched beam systems may not offer the degree of performance improvement offered by adaptive systems, but they are often much less complex and are easier to integrate into existing wireless technologies.

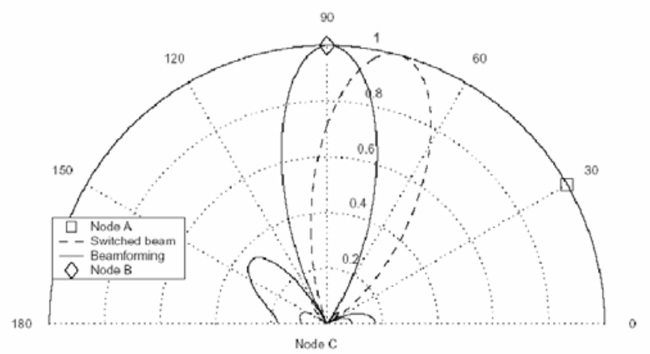

Figure 5.4 – Adaptive vs switched beams

Multihop networks with omni-directional antennas use a RTS/CTS (request to send/clear to send) floor reservation scheme that wastes a large portion of the network capacity by reserving the wireless media over a large area. As a consequence, a number of nodes in the neighbourhood of the transmitter and the receiver need to remain silent, waiting for the communication of the currently active nodes to be completed. The use of directional antennas (with fixed or adaptive beams) helps alleviate the problem by 'focusing' -through the use of narrow beams- transmission and reception on the nodes of interest only. As illustrated in Figure 5.5, nodes A, B, E and F have to be idle while nodes C and D communicate, when omni-directional antennas are employed. The use of directional antennas removes this constraint, provided that the nodes can be separated in space by shaping narrow beams.

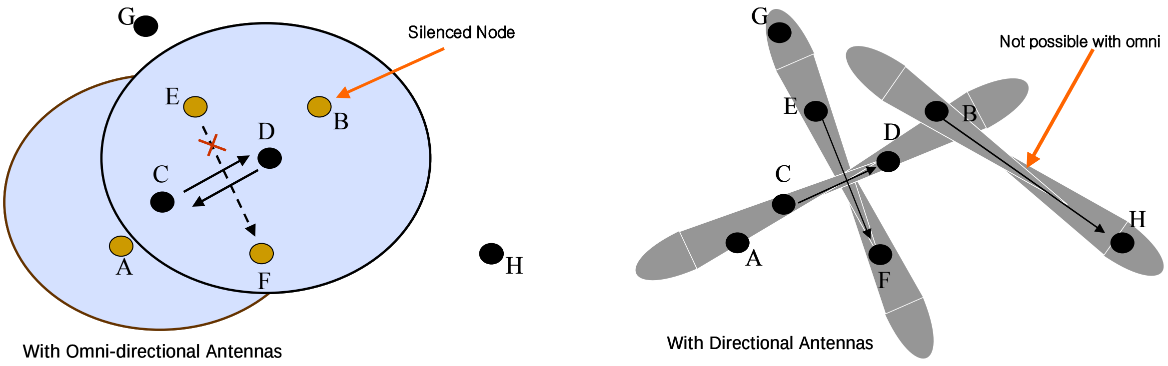

Figure 5.5 – Reduced interference and improved utilization of resources with directional antennas

5.5 Space-time coding

A transmitter equipped with multiple antennas can achieve transmit diversity by spreading the transmitted symbols over time and space (space-time coding). The amount of *transmit diversity* is equal to the smallest rank of codeword-error matrices, and the *coding gain* is related to the product of the non-zero singular values of these matrices [Tar98]. The specific design and implementation of the spreading depends on the level of channel knowledge at the transmitter and receiver.

Space-Time Trellis Codes (STTC) were originally proposed by Tarokh et al. in [Tar98] based explicitly on the above two criteria. In fact, this construction combines trellis coding and modulation design (including the mapping of the encoded data) with a redundancy expansion in both the signal and antenna space. The decoding complexity, however, becomes prohibitive with increasing constraint length. Furthermore, there is no systematic procedure for reducing the cardinality of the searched class of codes, and the codes do not demonstrate robustness in practical applications characterised by extremely variable Doppler frequencies.

Space-Time Block Codes (STBCs) –initially proposed in [Ala98]- spread the symbols in time and space in a block-by-block fashion. Among the class of STBCs, the so-called orthogonal STBCs, which are designed based on an orthogonal structure, are especially attractive because they dramatically reduce decoding complexity: via linear processing, joint maximum-likelihood decoding of all the transmitted symbols decouples into symbol-by-symbol decoding. The first orthogonal STBC, proposed by Alamouti for 2 transmit antennas, spreads the data (symbols x_1 and x_2) in time and space as

$$\mathbf{X}_{\text{Alamouti}} = \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix} \tag{5.1}$$

where rows and columns represent transmit antennas and symbol intervals, respectively. This simple code achieves full diversity and code rate 1, so that rate is preserved compared to the single antenna case. The basic construction of Alamouti generalises in the case of real-valued data symbols to arbitrary number of transmit antennas, and still retains full diversity and full rate equal [Tar99]. In the case of complex-valued data symbols, however, no full-rate codes exist for more than two transmit antennas. An example of full-diversity orthogonal STBCs with rate 1/2 and a four-element array can transmit 4 symbols over 8 symbol intervals according to:

$$\mathbf{X} = \begin{bmatrix} x_1 & -x_2 & -x_3 & -x_4 & x_1^* & -x_2^* & -x_3^* & -x_4^* \\ x_2 & x_1 & x_4 & -x_3 & x_2^* & x_1^* & x_4^* & -x_3^* \\ x_3 & -x_4 & x_1 & x_2 & x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & x_3 & -x_2 & x_1 & x_4^* & x_3^* & -x_2^* & x_1^* \end{bmatrix} \tag{5.2}$$

To achieve higher rates, one can sacrifice full-diversity, linearity or orthogonality. Sacrificing full-diversity gain was considered in [Jal99] where transmit-diversity 2 and rate 1 orthogonal STBCs were proposed for three and four antennas by applying a Walsh-Hadamard transformation to Alamouti codes. In the case of four transmit antennas, the corresponding code matrix is:

$$\mathbf{X}_{\text{Jalloul}} = \begin{bmatrix} x_1 & -x_2^* & x_1 & -x_2^* \\ x_2 & x_1^* & x_2 & x_1^* \\ x_3 & -x_4^* & -x_3 & x_4^* \\ x_4 & x_3^* & -x_4 & -x_3^* \end{bmatrix} \tag{5.3}$$

Sacrificing linearity was first considered in [Hoc00], in the context of unitary space-time modulations. The basic idea is to select a set of constellation points that lie in the hyper-surface of a unitary group manifold.

Finally, sacrificing orthogonality, which of course creates self-interference, has been studied for non-orthogonal or layered space-time block codes in [Tir01], quasi-orthogonal STBCs in [Pap01] and [Jaf01] and linear dispersion codes (LDCs) in [Has01]. Quasi-orthogonal STBCs with 4 antennas, the so-called ABBA code, achieves rate 1 and full diversity by permuting two Alamouti codes:

$$\mathbf{X}_{\mathrm{ABBA}} = \begin{bmatrix} x_1 & -x_2^* & x_3 & -x_4^* \\ x_2 & x_1^* & x_4 & x_3^* \\ x_3 & -x_4^* & x_1 & -x_2^* \\ x_4 & x_3^* & x_2 & x_1^* \end{bmatrix} \tag{5.4}$$

5.5.1 Reconfigurable STBC

Recent work based on the capacity analysis [Shi00] shows that in the presence of high fading correlations, transmission on the eigenmodes of the transmit antenna correlation matrix [Bru00] can be applied. The linear precoding technique proposed in [Sam02], which assumes knowledge of the antenna correlations at the transmitter, improves performance of a space-time coded system by forcing transmission on the nonzero eigenmodes of the transmit antenna correlation matrix. The main advantage of this precoder is that it does not have to track fast fading but only the slowly varying antenna correlations. The latter can be fed back to the transmitter using a low-rate feedback link or can be based on uplink channel estimation that exploits reciprocity. Furthermore, long-term channel knowledge contains only information on the antenna array response and ignores fast fading. The derivation of the linear precoding in [Sam02] was based on the average pair-wise error probability criterion. The design was then simplified by assuming that the worst pair dominates the performance. As it will be explained in the following sections, this assumption is no longer valid when the worst pair is not unique, i.e. two or more error pairs with different eigenmodes and energy distribution may result in the worst performance. This situation arises in the case of non-orthogonal STBC.

The objective is to design a *generic framework for reconfigurability in STBC through a linear precoding scheme applicable to any STBC type* (both orthogonal and non-orthogonal).

System assumptions: The communication system considered (Figure 5.6) consists of $\mathrm{M_T}$ transmit and $\mathrm{M_R}$ receive antennas. The transmitter is assumed to have some knowledge on the channel second order statistics. This information is available through the feedback bits sent by the mobile station or can be based on uplink channel estimation. As depicted in Figure 5.6, the space-time block encoder **X** maps the input data sequence $x=(x_1,x_2,..x_Q)$ into a $\mathrm{M_T} \times Q$ matrix **X** of codewords, that are split onto $\mathrm{M_T}$ parallel sequences. These codewords are then transformed by an $\mathrm{M_T}\times\mathrm{M_T}$ linear transformation **L** in order to adapt the code to the available channel information. The resulting sequences are sent on the $\mathrm{M_T}$ transmit antennas over Q consecutive time intervals (or Q adjacent subcarriers in an OFDM system where the channel is assumed to remain constant). Transmitted data are recovered at the receiver by means of a Maximum Likelihood (ML) receiver.

The channel is assumed to be block fading, i.e. it remains constant over a period of time ($\mathrm{T} > \mathrm{Q}$) large enough to allow the receiver to estimate the channel based on the training sequence and to perform a coherent detection of **X**. Each entry h_{ji} of the $\mathrm{M_R}\times\mathrm{M_T}$ channel matrix **H** represents the channel response between transmit antenna *i* and receive antenna *j*. The received signal is assumed to be a linear combination of several paths reflected from local scatterers, which introduces uncorrelated fading across the receive antennas and therefore uncorrelated rows of matrix **H.** However, limited scattering at the BS can introduce antenna correlation and therefore correlated columns of matrix **H**. According to the correlation-based model the channel **H** can be written as follows:

$$\mathbf{H} = \mathbf{H_W} \mathbf{R_T^{1/2}} \tag{5.5}$$

where $\mathbf{H_W}$ is an $M_R \times M_T$ i.i.d complex matrix and $\mathbf{R_T}$ is the $M_T \times M_T$ transmit antenna correlation matrix.

The received signal $\mathbf{Y}$ is corrupted by additive white Gaussian noise denoted by the $M_T \times Q$ matrix $\mathbf{V}$ with covariance matrix $\sigma^2 \mathbf{I}_{\mathbf{M_R}}$:

$$\mathbf{Y} = \mathbf{HLX} + \mathbf{V} \tag{5.6}$$

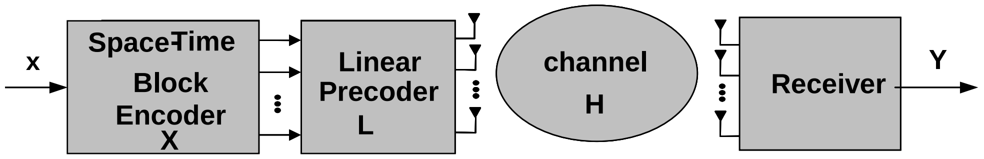

Figure 5.6 – Transmission scheme combining space-time block codes and a linear precoder that exploits channel knowledge available at the transmitter

Design criterion: The linear transformation $\mathbf{L}$ is determined by minimizing a given criterion, such as *an upper bound on the pair-wise error probability* (PEP) of the codeword [Sam02]. The PEP is defined as the error probability of choosing in favour of the codeword $\mathbf{X}^l$ instead of the actually transmitted codeword $\mathbf{X}^k$. The codeword $\mathbf{X}^l$ is given by:

$$\mathbf{X}^l = \arg\min_{\mathbf{X} \in Code} \left\| \mathbf{Y} - \mathrm{E}_s^{1/2}\mathbf{HLX} \right\|_F^2 \tag{5.7}$$

with E_s the symbol energy and $\| \ \|_F$ the Frobenius norm.

Let $\mathbf{E}(k,l) = \mathbf{X}^k - \mathbf{X}^l$ be the code error matrix. We define Ω as the set of non-zero code error matrices $\Omega = \{k,l : \mathbf{E}(k,l) \neq 0\}$. The *average* PEP denoted by $\overline{PEP}$ was upper-bounded in [Tar98] by:

$$\overline{PEP}(\mathbf{E}) \le \left[\det\left(\mathbf{I} + \frac{E_s}{4\sigma^2}\mathbf{R}_T^{1/2}\mathbf{LEE}^H\mathbf{L}^H\mathbf{R}_T^{1/2^H}\right)\right]^{-M_R} \tag{5.8}$$

where E_s is the symbol energy.

The design of the precoder should minimize the average pair-wise error probability of the worst error code matrix: $\min_{\mathbf{L}} \max_{\mathbf{E}} \overline{PEP}(\mathbf{E})$, as explained in [Med05]. In [Sam02] the worst performance was approximated by:

$$\max_{\mathbf{E}} \overline{PEP}(\mathbf{E}) \approx \overline{PEP}(\mathbf{E}_{\min}) \tag{5.9}$$

where $\mathbf{E}_{\min}$ is the code error matrix with the minimum determinant. This approximation works well if the Hermitian of $\mathbf{E}_{\min}$ ($\mathbf{E}_{\min}\,\mathbf{E}_{\min}^H$) is unique. If ($\mathbf{E}_{\min}\,\mathbf{E}_{\min}^H$) is not unique, for example $\mathbf{E}_1$ and $\mathbf{E}_2$ have the same minimum determinant but ($\mathbf{E}_1\,\mathbf{E}_1^H$) and ($\mathbf{E}_2\,\mathbf{E}_2^H$) are different, minimizing the averaged PEP of one of them does not ensure the performance of the other, and it can even degrade significantly $\max_{\mathbf{E}} \overline{PEP}(\mathbf{E})$ rather than improving it. To overcome this problem we introduce $\Sigma = \sup(\Omega^-)$, the matrix supremum of Ω^-, where $\Omega^- = \{\mathbf{M} / \mathbf{M} \le \mathbf{EE}^H, \forall \mathbf{E} \in \Omega\}$. If Σ is non-zero, we can write:

$$\min_{\mathbf{E}} \overline{PEP}(\mathbf{E}) \le \left[\det\left(\mathbf{I} + \frac{E_s}{4\sigma^2}\mathbf{R}_T^{1/2}\mathbf{L}\Sigma\ \mathbf{L}^H\mathbf{R}_T^{1/2^H}\right)\right]^{-M_R} \tag{5.10}$$

Linear precoder solution: The new upper bound on the PEP allows for a unique closed form solution for the linear precoder [Med05]:

$$\mathbf{L} = \mathbf{V}_T \Phi_{\mathbf{f}} \mathbf{V}_s{}^H$$
$$\Phi_{\mathbf{f}}^2 = \left(\gamma \mathbf{I} - \left(\frac{E_s}{4\sigma^2} \right)^{-1} \Lambda_T^{-1} \Lambda_s^{-1} \right)_+ \tag{5.11}$$

where $\mathbf{R}_T^{1/2} = \mathbf{U}_T \Lambda_T^{1/2} \mathbf{V}_T{}^H$ and $\Sigma = \mathbf{V}_s \Lambda_s \mathbf{V}_s{}^H$ are the Singular Value Decompositions of $\mathbf{R}_T^{1/2}$ and Σ respectively, $\gamma > 0$ is a constant computed from the trace constraint and $(\cdot)_+$ stands for $\max(\cdot,0)$.

The above expression for the linear precoder can be evaluated for any STBC provided that the spatial correlation is known. Analytical expressions for the linear precoder for commonly used STBCs are given in [Ale05] and [Med05].

Reconfigurability in terms of spatial correlation is achieved in the following sense:

- When the antenna correlation is zero (uncorrelated spatial modes), the eigenvalues of $\mathbf{R}_T^{1/2}$ are equal and the matrix of the eigenvectors equals the identity matrix. In this case, the linear precoder becomes an orthogonal transformation and the scheme is equivalent to STBC, which is the optimal approach for zero correlation.
- When the antenna correlation is one (fully correlated spatial modes), only one eigenvalue of $\mathbf{R}_T^{1/2}$ is non-zero and the precoder is equivalent to a beamformer, which is the optimal approach in this case.
- For partially correlated spatial modes the water-filling solution adapts to the relative power of the eigenmodes of $\mathbf{R}_T^{1/2}$ and Σ [Ale05].

The linear precoder for ABBA space-time block coding was studied in [Med05]. An urban micro channel model is used, based on the 3GPP Spatial channel model extended to 5GHz centre frequency and 20MHz bandwidth. The antenna array configuration is a 4 x 4 uniform linear array (ULA) with half wavelength spacing at the receiver and a linear array with [4,20,4] wave-lengths inter-element spacing at the transmitter. Constellations are either BPSK or QPSK. The channel code is the (561,731) convolutional code with ½ rate. We assume an OFDM system with 1024 subcarriers, of which only 832 are used for data transmission; the remaining subcarriers are reserved for the pilot.

In performance is depicted in terms of FER. Clearly, Linear Precoding outperforms both beamforming and ABBA without precoding. The curve of ‘Old-Linear Precoding’ refers to Linear Precoding based on the criterion proposed in [Sam02]. Constellation rotation is applied to the ABBA code according to [Sha03].

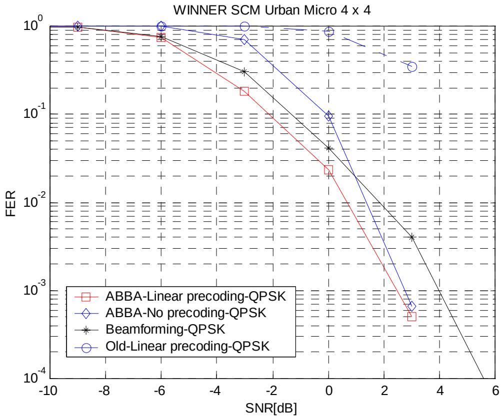

Figure 5.7 – Frame Error Rate performance for 4x4 system and Urban Micro environment

5.6 Spatial multiplexing

Spatial Multiplexing techniques transmit simultaneously independent data streams from different antennas. The input data streams are spatially multiplexed and, under favourable channel conditions, the spatial signatures of these transmitted streams are well separated. The receiver, having knowledge of the channel, can differentiate between these co-channel streams and extract each stream. The condition for spatial signature separation is that the channel matrix should have full rank, in which case the increase in transmission rate is linear in min(M, N), where M and N denote the number of transmit and receive antennas, respectively [Fos98]. A rank-deficient channel matrix, for example in a propagation environment with limited scattering, reduces the effective number of spatial signatures.

When CSI is not available at the transmitter, rate and power are equally distributed among the transmit antennas.

With CSI available at the transmitter, pre-coding may be applied in order to fully exploit the min(M, N) independent spatial modes (closed loop spatial multiplexing). Different modulation and coding schemes can be applied on each data stream to match the capacity of the corresponding sub-channel and maximise the throughput. In a water-filling approach for example, transmission is performed along the eigen-modes of the channel matrix [Gol03]. Ideally closed-loop spatial multiplexing techniques use the instantaneous channel knowledge at the transmitter and complex bit/power loading algorithms. When partial CSI is available, simpler approaches can be applied, such as the Per-Antenna Rate Control (PARC) [Luc02] and Selective-PARC [Eri04], where only simple indications of channel quality are signalled to the transmitter, enabling the selection of suitable modulation and coding scheme, transmit power levels, antenna selection and scheduling decisions.

Although through transmit diversity information is spread across multiple transmit antennas to maximise the diversity advantage in fading channels, with spatial multiplexing, the incoming data is divided into multiple substreams and each substream is transmitted on a different transmit antenna. For independent identically distributed (i.i.d.) Rayleigh matrix channels, spatial multiplexing can achieve the full ergodic capacity unlike diversity transmission [Has01][San00] but does not offer the same diversity gain as with MIMO diversity [Hea02]. The work in studies the multiplexing and diversity trade-off from an information-theoretic point of view based on achievable rates. In particular, it uses an approach based on an outage probability formulation that quantifies the amount of diversity gain and multiplexing gain achievable for any code.

5.6.1 Spatial link adaptation

Switching between multi-antenna techniques based on monitoring a certain channel metric at the receiver is often referred to as *spatial domain link adaptation*. For example, for rank-deficient channel matrices, the maximum number of distinct spatial signatures is not available and therefore full multiplexing gain is not achievable, whereas diversity gain maximisation may be possible. A straightforward metric in this case could be the rank of the channel matrix. In other words, the number of the singular values of the channel matrix that are substantially higher than the noise power characterise the effective rank.

In [Hea05], the *Demmel condition* was proposed as a suitable metric:

$$\kappa_D = \frac{\lambda_{\min}\left(\mathbf{H}\mathbf{H}^H\right)}{\|\mathbf{H}\|^2} \tag{5.12}$$

where $\lambda_{\min}$ is the smallest eigenvalue of $\mathbf{H}\mathbf{H}^H$ and $\|\mathbf{H}\|^2$ is the Frobenius norm of the channel matrix measuring the total power conveyed over all channel paths to the receiver. The performance of spatial multiplexing depends on the rank of the channel and is strongly determined by the minimum eigenvalue of $\mathbf{HH}^H$, whereas diversity is insensitive to the channel rank and only depends on the channel power measured by $\|\mathbf{H}\|^2$. It was shown in [Hea05] that spatial multiplexing outperforms the diversity method in terms of Euclidean distance if it is above a threshold

$$\kappa_D \geq \frac{d^2_{\min,sm}}{d^2_{\min,md}} \tag{5.13}$$

where $d^2_{\min,sm}$ and $d^2_{\min,md}$ are the minimum Euclidean distances in the transmit constellations of spatial multiplexing and MIMO diversity respectively. As the threshold κ_D increases more poorly conditioned channels become suitable for multiplexing.

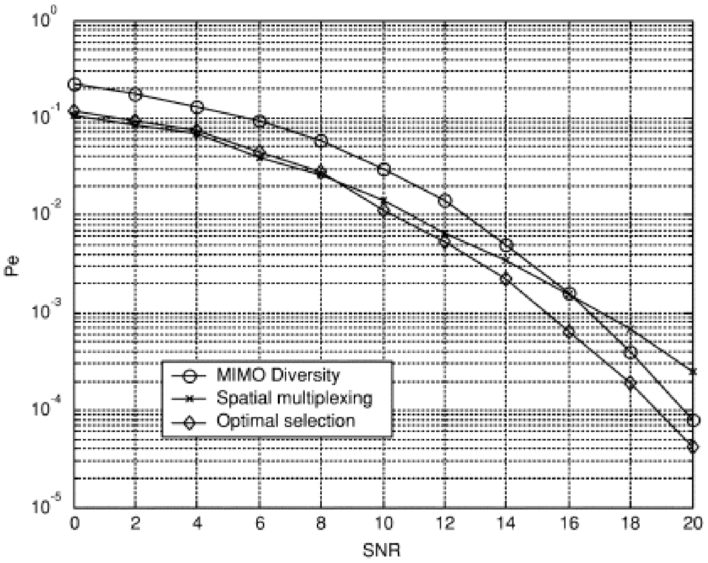

Figure 5.8 – Bit error rate versus SNR for 2X2 system with 4 bits/symbol and optimal selection of spatial multiplexing or MIMO diversity (source [Hea05])

The probability of bit error, averaged over all channel realizations, is illustrated in Figure 5.8 for fixed rate spatial adaptation that employs minimum Euclidean distance based switching. The encoder switches between the Alamouti MIMO diversity scheme [Ala98] with 16-QAM modulation and spatial multiplexing with 4-QAM transmit constellations. Spatial multiplexing performs better at low SNR but worst than MIMO diversity at higher SNR. This is due to the fact that spatial multiplexing has a diversity advantage on the order of the number of receive antennas, in this case second order, while MIMO diversity has a diversity advantage on the order of the product of the number of transmit and receive antennas, in this case fourth order. Diversity advantage changes the slope of the average probability for Rayleigh fading channels at high SNR. The MIMO diversity and spatial multiplexing curves cross at approximately 16 dB. Using the Demmel condition, it is possible to adapt based on the CSI and achieve the best of spatial multiplexing or diversity for each channel realization. The gain (over either spatial multiplexing or diversity) is about 1 dB at high SNRs and marginal at lower SNRs.

Spatial link adaptation requires instantaneous CSI at the receiver to be fed back to the transmitter. Quantization, feedback delay and channel estimation errors may affect the performance of spatial link adaptation and the right balance between performance and overhead signalling/complexity requirements needs to be identified.

Furthermore, spatial link adaptation criteria, like the one proposed in [Hea05], are usually characterised in a narrow-band sense. In the broadband case the decision would be based on clusters of subcarriers corresponding to the coherence bandwidth of the channel, and the metric value would be sent back for each cluster.

5.7 The multi-user case

In Sections 5.4-5.6 a number of multiple antenna techniques have been presented for the *optimisation of a single communication link*. Examples of reconfigurable approaches have also been discussed that exploit the availability of CSI in order to adapt to varying propagation and network conditions.

The optimisation of the multiple antenna, multiple link case (or the so called ‘multi-user’ case) has recently received increasing attention, based on the observation –mainly through system level analysis- that performance enhancements for a single communication link may not necessarily result in equivalent enhancements on the overall system performance. This is due to the fact that different links may be sharing (competing for) the same resources (e.g. time, frequency, code, space) or even when they do not, orthogonality may be destroyed due to propagation, synchronisation and other system impairments. Multi-link (multi-user) optimisation approaches are aimed to

- maximise the orthogonality with respect to radio resources among different links,
- reduce multiple access interference,
- improve the overall system level performance, in terms of throughput,
- introduce fairness in the distribution of resources and
- satisfy QoS constraints.

The selection of suitable multiple antenna, multiple link signal processing algorithms and radio resource management strategies depends on the constraints associated with the system design, the multiple access scheme in use, the network deployment, with implications in the interference scenarios, and the allowable computational complexity. Multiple antenna, multiple link optimisation techniques are classified into linear and non-linear, according to the type of processing. The former are usually less computationally complex but offer in general lower performance gains than the latter. Furthermore, the actual design should be tailored to ‘match’ the amount/quality of CSI available at the transmitter. When reliable CSI is available, beamforming schemes can be applied, whereas for limited or no CSI at the transmitter, techniques based on space-time codes or higher order statistics may be optimal.

5.7.1 Beamforming for multi-link optimisation

Multi-user beamforming is a form of SDMA, by allowing the transmission/reception of multiple beam patterns targeted to specific links utilizing the same time/frequency/code resources.

Beamforming requires high correlation of the signals or equivalently relatively low angular spread and few scatterers. Typical scenarios include outdoor nodes located above rooftop in urban or rural environments. Moreover closely-spaced antenna elements will increase the correlation of the signals and are therefore preferred for beamforming.

Similarly to the single link beamforming principles presented in Section 5.4, multi-user beamforming is designed according to certain *criteria for beam shaping*:

- Beam steering towards the directions of interest,
- SNR maximisation and
- SINR maximisation.

Allocation of beams to links is updated in a MEMBRANE wireless backhaul set up according to

- Spatial multiplexing and/or diversity scheme (multiple beams can be allocated to a single link),
- Scheduling strategy and
- Routing decision.

Both beam shaping and beam allocation decisions are based on the available short- or long-term CSI in terms of

- Beam selection metric (e.g. SNR)
- SINR report for each link
- Channel second order statistics (e.g. channel covariance)

In the case of *fixed beams* at each transmitting/receiving node a beamforming vector is selected from a predefined static set of antenna weights and therefore the antenna array patterns are fixed. Decisions are made on the beam (number of beams) allocation per link.

In the case of *adaptive beams* at each transmitting/receiving node the beamforming vectors are computed based on short- or long term CSI.

5.7.2 Opportunistic approaches in the multi-user case

In a multi-user context, the so-called opportunistic scheduling approaches have recently attracted considerable attention. The basic idea is to multiplex users by granting the channel to those with higher chances of completing a successful transmission and thereby achieve an overall, rather than individual link, throughput maximization.

For *specular spatial channels*, opportunistic beamforming (OBF) approaches [Vis02] point to the user with the highest SINR out of those present in the system. On the other hand, in *rich-scattering scenarios* opportunistic approaches will implicitly exploit fading by granting access to those with highest instantaneous capacity [Don03]. Instead of traditional strategies aiming at stabilizing individual links against channel (or interference) fluctuations by using multiple antennas, artificial fading may need to be introduced for slowly time-varying channels on the transmit side by randomly changing transmit weights. Opportunistic approaches go beyond the physical layer and exploit multi-user diversity as a complement to code, time, frequency or space diversity. This clearly has an impact on the design of MAC protocols, which need to evolve towards multi-user schemes, reinforcing the need for cross-layer designs.

OBF is a “natural” enhancement of opportunistic scheduling and consists in replacing the node antenna with multiple antennas and implementing an algorithm that generates a different beam every timeslot. In the case of “correlated environment” the beam sequence can be an orderly cyclic scanning of the desired sector with fixed angular steps, where K, the number of different beams, is a free parameter. We can then say roughly that each link (user) is “illuminated” every K timeslots.

OBF is particularly attractive, because no additional over-the-air signalling is required and the additional processing required at the receiver is minimal. However, the issue of delay and delay jitter was not considered, which is also a crucial parameter of a packet data access system. Satisfying QoS requirements of a typical data user amounts to providing sufficient average throughput, while satisfying certain packet delay constraints.

5.7.3 Opportunistic approaches exploiting cross-layer information

The overall system performance can be further enhanced by interacting with the higher layers of the OSI/ISO (Open Systems Interconnection model of the International Standards Organization) protocol stack. Multiple antenna techniques can be developed combining parameters in the physical, link and network layers, i.e. in a cross-layer fashion rather than attempting to optimize the designs in isolation of one another.

The information to be exchanged among the functionalities residing in different OSI layers mainly concerns CSI, QoS-related parameters, such as delay, and physical layer resources, such as antenna array configuration and spatial processing options.

In this framework, Joint Opportunistic Beamforming and Scheduling (JOBS) was proposed [Avi04]. JOBS combines channel aware scheduling with “dumb” beamforming [Vis02]. The delay constraint is considered in terms of the probability that the inter packet delay exceeds a certain threshold. When such an event occurs, we call it a delay outage. In this context, improving the delay performance amounts to reducing the probability of delay outage.

The beam-generating algorithm attempts to use system state information and modifies the beam scanning sequence accordingly. Past and present feedback reports along with the waiting times are used as system state information. The “preferred beam” is determined by averaging the reports fed back in response to transmissions of pilot signals on each of the beams.

JOBS is particularly attractive, because no additional signalling is required and the additional processing required at the receiver is minimal. In packet data systems there is a trade off between throughput and delay. When the throughput gains, the delay performance deteriorates. The delay performance can be dramatically improved and at the same time the throughput is also improved by employing JOBS algorithm, which exploits all past reports to “learn” the current preferred beam for each user (link), and puts this information to use by providing priority to users (links) waiting longer for the next packet. Simulations demonstrated improved performance in several scenarios [Avi04].

5.7.4 Optimised beamforming and scheduling exploiting CSI

OBF exploits the multi-user diversity under a reduced feedback requirement and keeps the receiver simple and transparent to the use of multi-transmit antennas. The OBF uses a varying beamformer to enhance multi-user diversity. The scheduler decision is then made on the basis of the feedback information. Jointly Opportunistic Beamforming and Scheduling combines OBF with fixed grid of beams (instead of the varying beam) and quality of service based scheduling. It is important to observe, however, that the delay between the feedback measurements and the transmission made on the basis of these measurements is not carefully considered. During this delay interval the channel can change significantly; therefore, taking into account this delay can have an impact on the performance and could lead to different conclusions.

A new technique was proposed [Med06] to perform optimal beamforming while keeping all the advantages of OBF, namely a simple receiver and a reduced feedback rate. The technique proposes to utilize the same amount of feedback for the quantization of the equivalent single transmit antenna channel seen by each user. This feedback is used by a Kalman tracking filter to deliver a channel estimate in the form of average and covariance for each user. The channel estimate is then used to evaluate the maximum expected throughput used for the scheduling algorithm, and once a user is scheduled for a transmission it is also used to evaluate the optimal beamformer.

The channel tracking in this setting is made possible by the low dynamics (variations) of the channel and the availability of the feedback for different dimensions (projections of the channel). The feedback of different dimensions is provided by the transmission (scheduling) to different users. On the other hand, the low dynamics allows the combination of these different feedbacks, in an adaptive real time fashion, in order to deliver a channel estimate.

Let us assume that a node serves K links (users) that are competing for the same resources, but at a given time the node transmits to one link (user) only. The node has N_t antennas and the transmission is performed in time slots of size T. The different channels are considered to be constant during a time slot but can change from a time slot to another.

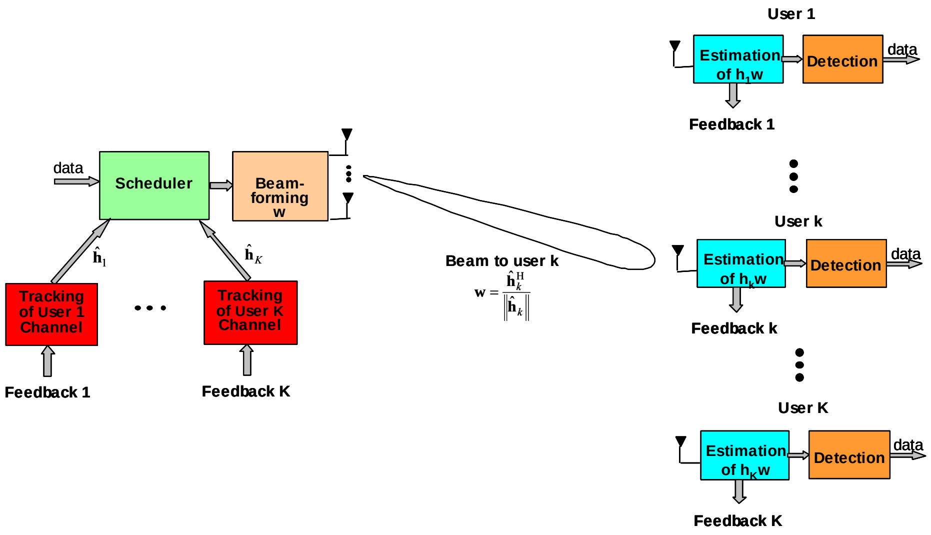

Figure 5.9 – Block diagram describing the concept of optimized multi-user beamforming with channel tracking

We assume that the receiving node has one receive antenna but the analysis can be easily generalised to multiple receive antennas. In the baseband complex representation, the received signal, $\mathbf{y}_k(n): 1\times T$, at the k$^{\text{th}}$ user (k=1…K) is

$$\mathbf{y}_k(n) = \mathbf{h}_k(n)\mathbf{w}(n)\mathbf{x}(n) + \mathbf{v}_k(n)\,, \tag{5.14}$$

where $\mathbf{x}(n): 1\times T$ is the input signal to the beamformer, $\mathbf{w}(n): \mathrm{N_t}\times 1$ is the normalized beamforming vector ($\|\mathbf{w}(n)\|^2 = 1$), $\mathbf{h}_k(n): 1\times \mathrm{N_t}$ is the k$^{\text{th}}$ user channel at time slot n and the noise $\{\mathbf{v}_k(n): 1\times T\}_{\mathrm{n,k}}$ is i.i.d. random sequence following a zero-mean complex Gaussian distribution with variance σ^2.

The transmitted power is fixed to P and the Signal to Noise Ratio (SNR) is denoted by $\rho = \dfrac{\mathrm{P}}{\sigma^2}$.

In order to study the effect of channel variation (delay), we assume that the channels of different users vary in time following an autoregressive model. For such a model the channel is a linear combination of the past realizations plus an innovation term.

The simplest model (and at the same time the one that requires the least *a priori* information) is the AR(1), according to which the state evolution equation of the channel is

$$\mathbf{h}_k(n) = \lambda_k \mathbf{h}_k(n-1) + \mathbf{u}_k(n) \tag{5.15}$$

where λ_k is a complex parameter related to the channel dynamics $|\lambda_k| < 1$, and $\mathbf{u}_k(n) \sim CN(0, \sigma^2_{\mathbf{u}_k}\mathbf{I}_{\mathrm{Nt}})$ is the innovation following a zero mean complex Gaussian distribution with covariance $\sigma^2_{\mathbf{u}_k}\mathbf{I}_{\mathrm{Nt}} = (1-|\lambda_k|^2)\sigma^2_{\mathbf{h}_k}\mathbf{I}_{\mathrm{Nt}}$.

Two major problems arise in this multi-antenna and multi-user context. The first is how to schedule the transmission to different users so as to optimize the network performance when keeping fairness between users. The second is the design of the beamformer given the reduced feedback rate. The first problem can be solved by the use of the proportional fair scheduling. For the design of the beamformer, the opportunistic beamforming [Vis02] proposes the use of a random and time varying beamformer.

The *Proportional Fair Scheduling (PFS)* was proposed in order to ensure fairness in the allocation of resources among users, under a maximum delay constraint of T_c time slots. In this algorithm each user has a requested data rate $R_k(n)$, evaluated based on the feedback from the user terminal to the BS. The scheduling algorithm decides to transmit to user k* with the largest ratio $\frac{R_k(n)}{T_k(n)}$, among all active users.

$$k^* = \arg\max_k \frac{R_k(n)}{T_k(n)}, \tag{5.16}$$

$T_k(n)$ is the average throughput updated as follows

$$T_k(n+1) = \begin{cases} (1-\frac{1}{T_c})T_k(n) + \frac{1}{T_c}R_k(n), & k = k^* \\ (1-\frac{1}{T_c})T_k(n), & k \neq k^* \end{cases} \tag{5.17}$$

Although inherently the PFS algorithm assumes that the user channels vary smoothly enough for $R_k(n)$ to be roughly the same from one slot to the following, the algorithm works particularly well in a dynamic environment and is less efficient in the case of a slowly varying environment where the channel fluctuation is of a small magnitude.

In the opportunistic beamforming $\mathbf{w}(n)$ is a random time varying sequence, which is independent of the feedback and the scheduling decision. This choice of $\mathbf{w}(n)$ artificially increases the channel dynamics. The sequence $\mathbf{w}(n)$ is assumed to vary slowly enough, for the overall channel gain, $|\mathbf{h}_k(n)\mathbf{w}(n)|$, to remain roughly the same from one slot to the next. For each user, the feedback quantifies $|\mathbf{h}_k(n-1)\mathbf{w}(n-1)|$, and the PFS then applies by assuming a requested data rate equal to the channel capacity

$$R_k(n) = \ln_2(1+\rho|\mathbf{h}_k(n-1)\mathbf{w}(n-1)|^2) \tag{5.18}$$

The idea behind using a random beamformer is to avoid the feedback of the full channel, which can result in significant overhead signalling requirements, especially in the case of the use of multiple antennas, thus, allowing a limited number of bits for the feedback of one coefficient that corresponds for instance to the requested data rate. If we assume now that this limited amount of feedback signalling is allocated to the feedback of the equivalent channel complex gain $\mathbf{h}_k(n)\mathbf{w}(n)$, then, the node can exploit these feedbacks and its knowledge on the sequence of beams $\mathbf{w}(n)$ to track the channels of the different users. For each link, the channel estimate can then be used to perform optimal beamforming using the maximum ratio combining (MRC) solution.

According to the proposed technique, each user sends the complex gain $\mathbf{h}_k(n)\mathbf{w}(n)$ to the transmitting node. This feedback is used to perform channel tracking per link at the node. The channel estimate given by the tracking is used to perform the scheduling and then to transmit by applying the MRC beamformer.

At the receiving node estimates of the channel gain are evaluated and sent as a quantized feedback report to the transmitting node. We denote this report by $\alpha_k(n)$. Due to the delay involved in the feedback process, $\alpha_k(n)$ corresponds to the estimate of $\mathbf{h}_k(n-1)\mathbf{w}(n-1)$

$$\alpha_k(n) = \mathbf{h}_k(n-1)\mathbf{w}(n-1) + \eta_k(n) \tag{5.19}$$

where $\eta_k(n) \sim CN(0,\sigma_\eta^2)$ accounts for the estimation and quantization error of the complex gain.

The channel tracking can be performed, with low computational complexity, using a Kalman filtering algorithm [Med06]. The Kalman filter delivers an estimate $\hat{\mathbf{h}}_k(n)$ and an error covariance (quality of the estimate) $\hat{\mathbf{C}}_k(n)$

$$\hat{\mathbf{C}}_k(n) = \mathrm{E}[(\mathbf{h}_k(n) - \hat{\mathbf{h}}_k(n))^{\mathrm{H}}(\mathbf{h}_k(n) - \hat{\mathbf{h}}_k(n))] \tag{5.20}$$

The estimate of the channel of each link allows the use of the optimal beamforming instead of the opportunistic one. The MRC beamforming vector $\mathbf{w}(n) = \dfrac{\hat{\mathbf{h}}_k^{\mathrm{H}}(n)}{\left\|\hat{\mathbf{h}}_k(n)\right\|}$ is used.

The PFS is now applied based on the requested throughput $R_k(n)$

$$R_k(n) = \max_{R\geq 0} R\left[1 - P_{out}(R|\hat{\mathbf{h}}_k(n), \hat{\mathbf{C}}_k(n))\right] \tag{5.21}$$

where the outage probability is evaluated conditioned on the past received feedback information

$$P_{out}(R|\hat{\mathbf{h}}_k(n), \hat{\mathbf{C}}_k(n)) = \\ \Pr\left[\log(1+\rho\frac{\left|\mathbf{h}_k(n)\hat{\mathbf{h}}_k^{\mathrm{H}}(n)\right|^2}{\left\|\hat{\mathbf{h}}_k(n)\right\|^2}) \leq R|\hat{\mathbf{h}}_k(n), \hat{\mathbf{C}}_k(n)\right] \tag{5.22}$$

The maximization in the computation of the rate can be performed numerically. Thanks to the low dynamics of the channel, which applies also to ($\hat{\mathbf{h}}_k(n), \hat{\mathbf{C}}_k(n)$), the rate $R^{k,\max}(n)$ that achieves the maximum for time instant n can be written as a small deviation of $R^{k,\max}(n-1)$: $R^{k,\max}(n) = R^{k,\max}(n-1) \pm \Delta$. This simplification allows to restrict the maximization to the evaluation over two values only, namely $R = R^{k,\max}(n-1) + \Delta$ or $R = R^{k,\max}(n-1) - \Delta$.

Simulation results presented in [Med06] show that the proposed optimised multi-user beamforming with channel tracking achieves important spectral efficiency gains by performing the optimal beamforming and exploiting the muti-user diversity. It also keeps the receiver design simple. The optimized multi-user beamforming with channel tracking outperforms opportunistic beamforming and shows high robustness to the feedback delay and quantization.

The novel beamforming and scheduling approach presented in this section is an example of cross layer optimisation: both the spatial processing through beamforming and the scheduling are jointly optimised exploiting the available CSI and making use of channel tracking.

5.7.5 Precoding for multi-link optimisation

Precoding, in the multi-user context, is used to denote the efficient elimination or suppression of multi-user interference via beamforming presented in the previous sections, or ”dirty-paper” codes ([Taf06] and references therein).

Block diagonalization (BD) is a *linear pre-coding technique* that decomposes a multi-user MIMO channel into multiple parallel orthogonal single-user MIMO channels. The signal of each user is pre-processed at the transmitter using a modulation matrix that lies in the null space of all other users’ channel matrices. Thereby, the multi-user interference in the system is efficiently set to zero. BD is attractive if the receiver is equipped with more than one antenna. However, the zero multi-user interference constraint can lead to a large capacity loss when the users’ subspaces significantly overlap.

Minimum mean-square-error (MMSE) precoding improves the system performance by allowing a certain amount of interference especially for receivers equipped with a single antenna. However, it suffers a performance loss when it attempts to mitigate the interference between two closely spaced antennas. In [Sta04] a new algorithm is proposed called successive MMSE (SMMSE) which deals with this problem by successively calculating the columns of the precoding matrix for each of the receive antennas separately. The complexity of this algorithm is only slightly higher than the one of BD but it can provide a higher diversity gain and a larger array gain than BD.

In the same way as linear equalization, linear precoding suffers from noise enhancement and hence poor power efficiency. This disadvantage of linear equalization at the receiver side can be avoided by decision-feedback equalization (DFE). Tomlinson-Harashima precoding (THP) is a *non-linear pre-coding technique* developed for single-input, single-output (SISO) multipath channels. THP can be interpreted as moving the feedback part of the DFE to the transmitter. Recently it has been also applied for the pre-equalization of multi-user interference in MIMO systems [Cin00], where it performs spatial pre-equalization instead of temporal pre-equalization. Thereby, no error propagation occurs. Hence, the precoding can be performed for the interference-free channel. MMSE precoding in combination with THP is proposed in [Joh04]. MMSE balances the multi-user interference in order to reduce the performance loss that occurs with zero interference techniques while THP is used to reduce the multi-user interference and to improve the diversity. SO THP proposed in [Sta05] combines successive optimisation and THP in order to reduce the capacity loss due to the cancellation of overlapping subspaces of different users and to eliminate the multi-user interference.

5.8 Baseline techniques in MEMBRANE

In MEMBRANE two multiple antenna baseline techniques will be considered for the studies:

- **Multiple antenna processing baseline 1**: fixed directional antenna pointing to each neighbour in the backhaul topology. Each transmit (receive) beam is x degrees wide, centered on the receiver (transmitter). There is no interference at angles beyond this beamwidth (ideal array pattern). The capability of ‘illuminating’ simultaneously multiple beams will be assumed available.
- **Multiple antenna processing baseline 2**: Alamouti STBC [Ala98].

The first baseline technique addresses the case where optimisation of the received/transmitted power in space is an objective. The second baseline technique is targeting the optimization of link quality in the presence of fading.

6 SCHEDULING AND ROUTING CONSIDERATIONS

6.1 Wireless backhaul considerations

Wireless multihop networks are easy to deploy and expand incrementally, can adjust to failures or changing traffic demands by reconfiguring backhaul routes, and can provide ubiquitous service. Furthermore, multihop allows to reduce the distances between nodes. This can help increase network throughput due to lower pathloss and better spatial reuse. However, several challenges remain in ensuring that multihop wireless backhaul networks can match the throughput and delay guarantees of wired backhaul networks. Although multihop can help boost throughput, the network must now be more carefully *scheduled to reduce interference* and *maintain satisfactory delay performance* (in terms of average delay and jitter) over multiple hops. In particular, providing guaranteed rates while keeping end-to-end delays low is necessary for any backhaul network that will carry delay sensitive traffic (such as VoIP, video and interactive applications).

There are two types of interference in our backhaul network: (a) self-interference that prevents a single node from simultaneously transmitting and receiving, or from simultaneously receiving from multiple neighbours on the same subchannel; and (b) cross-link interference, caused by transmissions using the same subchannel over two separate links with distinct receivers that are located close to each other.

The routing and scheduling components design (to be investigated in detail in the Deliverable 4.2) must aim to avoid such interference while maximizing throughput and minimizing delay. The routing component finds routes for each node to and from the gateway. Presumably, given the set of routes, the scheduling component needs to supply two parts: (a) a link activation scheme that specifies the set of links that are active at each timeslot along with the set of subchannels they use, and (b) a scheduling policy that determines the set of packets to be transmitted along an active link(s) at each time slot.

In our backhaul network, schedule and routing are in fact highly dependent to each other. In particular, use of opportunistic scheduling algorithms offers potential multi-user diversity gain in terms of improved link capacity (and thus performance). Note that link capacity in our wireless backhaul network is not fixed and known in priori for a given network topology. Instead, it depends on the specific scheduling algorithm in use, the cross-link interference, and the amount of traffic load a node has to forward to its next hop nodes (neighbours). Clearly, the routing algorithm affects the latter two factors. Ideally, the joint optimised scheduling and routing algorithm will consider all factors involved in order to provide the best possible performance.

For networks with a relatively small number of nodes, one can develop a centralized algorithm for the joint scheduling and routing by assuming that appropriate channel and traffic information is available. However, due to the high computation complexity and the excessive amount of exchange of channel/traffic information, it is not feasible to extend and apply the centralized algorithms to large-scale networks. It does seem that a distributed scheme, which may not necessarily achieve the optimal performance, but can deliver robust and good performance will represent a reasonable approach.

Another important aspect of the joint scheduling and routing algorithm for the MEMBRANE is the cross-layer optimization. Specifically, given the opportunistic nature of the algorithm, the activation and capacity of a particular link may fluctuate greatly in time. In such environments, existing work (e.g., [Kle04]) has shown that throughput performance at the transport level may suffer. Special attention should be given to ensure that the joint scheduling and routing algorithm will not generate negative impacts on the transport-level performance. This aspect will be addressed in detail in the Deliverable 4.3.

6.2 Spatial scheduling

SDMA in the context of MEMBRANE will allow nodes to have simultaneous reception or transmission of multiple packets enhancing the network throughput substantially. For simultaneous transmissions, the use of multiple "beams," each targeting at different receiving node, provides additional flexibility in avoiding the cross-link interference, thus potentially offer significant capacity improvement. For SDMA to achieve the maximum performance gain, a spatial scheduling scheme is required based on a measure of 'separability' between nodes, which is characterized by the angular separation of beam directions and the anticipated link quality for different receivers.

Nodes are assumed equipped with spatial multiplexers and demultiplexers. The scheduling algorithm on each node keeps track of its adjacent nodes, their degree of separability and the quality of the associated links. In addition, the SDMA scheduler also takes advantage of link fluctuation, which is mainly due to cross-link interference instead of fading in mobile environments, among various adjacent nodes to achieve multi-user diversity gain, while maintaining some form of fairness such as proportional fairness.

6.3 Opportunistic routing

For the efficient design of the wireless backhaul, the satisfaction of the network delay AND throughput requirements are our priority. Multiple antenna processing and SDMA can further increase the end-to-end throughput and delay by exploiting the spatial dimension.

Opportunistic (also called reconfigurable) routing takes into account network context and topology parameters, such as the quality of different links, the data traffic needs on different nodes, the capacity of different relays, the packet activity of different links, etc. Opportunistic routing could take advantage of the fact that in a wireless network transmitted packets may be heard by multiple neighbours at the radio level. Instead of choosing a single route ahead of time, opportunistic routing would determine the path as the packet moves through the network.

In MEMBRANE opportunistic routing will also exploit the spatial dimension, in terms of reconfigurable transceiver link optimisation, directional transmission to different nodes, spatial multiplexing and SDMA.

Along these lines the extra benefit of spatial data splitting. First the investigation of the impact of spatial data splitting on the QoS of jointly optimised routing / scheduling algorithms will be carried out. Based on the conclusions of this study, efficient opportunistic spatial data splitting techniques will be developed, in order to improve end-to-end QoS.

6.4 Adaptation time scales

Adaptation in MEMBRANE studies will be considered in the following three time scales:

- **Network topology adaptation** represents the update frequency of routing decisions. Between two consecutive routing decisions the topology of active nodes is considered fixed.
- **Scheduling adaptation** represents the update frequency of scheduling policy decisions. These decisions are made based on the interference limitations, satisfying throughput-delay requirements and optimising link capacity and performance.
- **Physical layer reconfigurability** represents the adaptation of multiple antenna transceivers to both short-term (e.g. fast fading) and long-term CSI and interference variations.

7 CONCLUSIONS

In this report, we have first determined different propagation scenarios along with their corresponding parameters. The scenarios have been separated into the Urban and Rural areas. In the Urban scenario, three sub-categories (U1, U2, U3) have been identified, while in the Rural area, two sub-categories (R1, R2) have been determined. Then, different channel models have been proposed to model these different sub-categories respectively. Models from WINNER Project have been used for similar urban scenarios U1, U2, R2. The 3GPP /3GPP2 SCM model and its extended version SCME has been suggested to be used in scenario R2 and U3 with some modifications, while models for scenario R1 still need to be developed.

To model the interference in a multi-hop wireless backhaul network, a ‘regular’ network topology with hexagonal cells has been proposed, where the AN is surrounded by rings of INs. Assuming that only the nodes on adjacent rings can communicate with each other, we have suggested to only consider the first ring of strongest interferers that communicates simultaneously as the interference.

We have discussed the parameters and performance metrics in the physical layer. Both the system parameters and scenario parameters have been determined in this report, which will be used in the future simulations. The performance metrics have been discussed on both the link level and system level. Different metrics have been proposed and will be used to test different algorithms developed in the MEMBRANE Project.

Different multiple antenna techniques have been discussed in this report. Details on MIMO transceiver architecture, intelligent antennas, space-time coding, spatial multiplexing and OB have been described respectively. The principles of reconfigurable multiple antenna transceiver design have been presented, as means to provide adaptivity to varying propagation conditions, either through the introduction of linear precoders or through spatial adaptation. The importance of exploitation of channel state information has also been discussed. Furthermore, two multiple antenna baselines have been proposed for performance comparison.

Discussion on scheduling and routing in a wireless backhaul network has also been given. It has been concluded that the main target for scheduling and routing is to avoid the interference while at the same time maximizing the throughput and minimizing the delay. Finally, spatial scheduling, spatial routing and adaptation have been briefly described at the end of this report.

Overall, this report has set the ground for the MEMBRANE Project in terms of physical layer parameters, scenario setups, and channel modelling. Some major candidates for the multiple antenna reconfigurable transceiver design have also been described, and further research will be carried out based on these studies.

TERMS AND ACRONYMS

AN	Access Node
AoA	Azimuth of Arrival
AoD	Azimuth of Departure
AWGN	Additive White Gaussian Noise
BD	Block Diagonalization
BER	Bit Error Rate
BO	Basis vector offset
BS	Base Station
CDL	Clustered Delay Line
CSI	Channel State Information
DFE	Decision Feedback Equalizeer
DoA	Direction of Arrival
DoD	Direction of Departure
DVB	Digital Video Boardcasting
EN	End Node
HARQ	Hybrid Automatic Repeat Request
IA	Intelligent Antennas
IN	Intermediate Node
ISI	Intersymbol Interference
JOBS	Joint Opportunistic Beamforming and Scheduling
LDC	Linear Dispersion Code
LOS	Line-of-sight
MIMO	Multiple Input Multiple Output
MISO	Multiple Input single Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combining
MS	Mobile Station
MSI	Multi-stream Interference
OA	Offset Angle
OBF	Opportunistic Beamforming
OFDM	Orthogonal Frequency Division Multiplexing
PARC	Per-Antenna Rate Control
PAS	Power Angle Sprectrum
PEP	Pair-wise Error Probability

PER	Packet Error Rate
pdf	Probability Density Function
PFS	Proportional Fair Scheduling
QoS	Space Division Multiple Access
SCM	Spatial Channel Model
SDMA	Space Division Multiple Access
SINR	Signal-to-Interference plus Noise Ratio
SIR	Signal-to-Interference Ratio
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
STBC	Space-time Block Code
STTC	Space-time Trellis Code
SUI	Stanford University Interim
THP	Tomlinson-Harashima Precoding
ToA	Time of Arrival
ULA	Uniform Linear Array
V-BLAST	Vertical Bell labs Layered Space-Time
ZF	Zero Forcing

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