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Deliverable D6.1

Final MEMBRANE Project Report: Multi-Element Multihop Backhaul Reconfigurable Antenna Network - Performance evaluation and recommendations

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Abstract:

This Deliverable presents the innovative concepts, methodologies, algorithms and platforms/prototypes devised/developed in the MEMBRANE projects and summarises the most important results and conclusions drawn on their performance and complexity merits. Based on these conclusions, recommendations for the efficient design of the MEMBRANE network are provided and the associated challenges are discussed.

EXECUTIVE SUMMARY

In this final MEMBRANE report we present the objectives, approach, major achievements and innovations, the developed tools and obtained performance gains and the final conclusions and recommendations drawn from the performed studies.

The increasing requirements for highly performing and efficiently deployable backhaul networks motivated the basic MEMBRANE objective, for the development of a powerful alternative to existing backhauling solutions, based on the use of multi-antenna, multihop, cross-layer optimised architectures. Towards this objective, two target scenarios have been identified: the remote rural scenario with limited/insufficient backhaul infrastructure and the ‘data-hungry’ urban scenario where increasing backhauling requirements cannot be addressed with legacy infrastructure and its potential extensions (e.g. fibre) may not be economically attractive solutions.

The MEMBRANE studies focus on the analysis of the fundamental performance of multihop (MIMO) networks, the development of multi-antenna and multihop transmission schemes for throughput maximisation, the design of jointly optimised scheduling, routing and power control mechanisms, the adaptation of the existing Transmission Control Protocol algorithms to the wireless multi-hop backhaul network and the development of a software system level evaluation platform and a proof-of-concept prototype for performance assessment:

- The analysis of the fundamental performance of multihop (MIMO) networks provides system design guidelines for future cooperative communication schemes. The asymptotic (in number of relays) network capacity results obtained can be used to estimate the throughput of a large relay network. Furthermore, the derived trade-off between the channel state information required at relay level and the number of relays that must exist in the network in order to mitigate the effects of interference and fading can be used to assess the number of relays to be deployed or the amount of channel training required in the system. Finally, the asymptotic (in signal-to-noise ratio) analysis provides a code design criterion to achieve optimal performance.
- The novel concept of Data Splitting algorithm (DSA) is proposed as a means of multi-antenna signalling and routing, according to which independent streams are “routed” to different relays and at the same time sent directly to the destination in order to maximize the throughput, taking advantage of both the spatial and relay degrees of freedom. Throughout the studies of DSA and other multi-antenna relaying alternatives it is concluded that the deployment and propagation scenarios play a very important role in the selection of the optimal scheme.
- With regards to scheduling and routing, the theoretical studies and analysis of the Proportional Fair Scheduler provide guidelines and analytical support on system design, simulation-based modelling and performance analysis in the context of cross-layer design for wireless mesh networks. Furthermore, the developed joint scheduling and QoS routing cross-layer scheme has been proven able to guarantee multi-constraint QoS for a wide range of applications, while at the same time exploit the multi-user diversity gain. Finally, the proposed QoS MIMO routing algorithm can be easily applied to any multi-hop system of wireless MIMO transceivers.
- The IP network design studies in the framework of MEMBRANE aim to propose and analyse methods for optimizing existing TCP (Transmission Control Protocol) performance in a reconfigurable multi-antenna, multi-hop wireless backhaul network

context. In that respect, a number of cross layer approaches were devised and assessed in an integrated (layers 1-2-3-4) simulation environment with respect to a number of parameters, such as the number of flows and hops, the MAC schemes and interference scenarios.

- The MEMBRANE system level simulation platform has been developed in order to assess and compare a number of multi-antenna and relaying protocols and their efficiency in a number of propagation scenarios. Based on this realistic system level performance analysis, recommendations can be provided on the optimal MIMO and multihop signalling in different deployment scenarios.
- The MEMBRANE proof-of-concept prototype has been developed to operate in two distinct modes: a centralized one using the DSA algorithm and a de-centralized mode employing the MEMBRANE Distributed Scheduling (MDS) protocol. Performance gains were illustrated and implementation aspects, including complexity assessment, were investigated.

The ideas, concepts, algorithms, methodologies and tools developed in the framework of MEMBRANE have been broadly disseminated by means of international conferences papers, journal publications and standards contributions and largely exploited by both the academic and industrial participants in their teaching/research and technology assessment activities respectively.

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ART	Above rooftop
BER	Bit Error Rate
BLER	Block Error Rate
BRT	Below rooftop
CAC	Connection Admission Control
DSA	Data Splitting Algorithm
DSL	Digital Subscriber Line
ECN	Explicit Congestion Notification
ELN	Explicit Loss Notification
ERN	Explicit Rate Notification
FTTH	Fibre to the home
HLLE	Hardware Link Level Emulator
IPC	Independent Power Constraint
LLS	Link Level Simulation
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MDS	MEMBRANE Distributed Scheduler
MET	Multiuser Eigenmode Transmission
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
PER	Packet Error Rate
PFS	Proportional Fair Scheduling
PHY	Physical Layer
QoS	Quality of Service
SIR	Signal to Interference Ratio
SISO	Single Input Single Output
SLS	System Level Simulation
SNR	Signal to Noise Ratio
SPC	Sum Power Constraint
SVD	Singular Value Decomposition
TCP	Transmission Control Protocol

TDD	Time Division Duplex
TDMA	Time Division Multiple Access

1 Introduction and scope

The ongoing proliferation of wireless broadband data services and the introduction of new technological advances, such as network coordination, are expected to lead to increased demand on the backhaul networks. The backhaul networks transfer data between wired Internet and communication nodes from which end users are connected by radio links. The typical upgrade of wired lines to high-speed fibre networks may not always be available or economically attractive solution for the backhaul networks. In such cases, wireless approaches could offer an appealing alternative. In MEMBRANE we propose the design of reconfigurable multi-antenna, multihop wireless backhaul networks that meet the Quality of Service demands of high-speed access networks, thus providing a technology shortcut to help satisfy the social need for broadband data anytime anywhere in a much more expeditious way for European users, including those in less developed, peripheral and rural areas.

In order to provide cost-efficient wireless backhaul with low deployment costs and flexible provisioning, the proposed approach relies on an adaptive, multihop networking design that makes use of channel state information and interference optimised resource allocation and routing. A range of novel techniques, such as intelligent antenna or MIMO (Multiple-Input-Multiple-Output)-enabled routing and jointly optimised scheduling and routing, allow for efficient and dynamic network management, which can improve Quality of Service and revolutionalise network resilience, deployability and adaptability. Since wireless broadband access networks employ several technologies, the proposed backhaul network is designed to match these heterogeneous networks such that it can work in an agnostic way with respect to the employed access technology. The potential performance gains of the new backhaul network have been assessed through theoretical studies, simulations and proof-of-concept prototyping and demonstration.

The scope of this final MEMBRANE project report is, first, to summarise the MEMBRANE approach in terms of scenarios investigated, theoretical frameworks studied, algorithms developed and evaluation methodologies followed (chapter 2). Then, a comprehensive presentation is provided of the major achievements during the course of the project, in terms of analysis, ideas and concepts, algorithms and systems design innovations, performance evaluation methodologies and performance improvements (chapter 3). Finally, the findings, conclusions on the impact of various parameters and performance tradeoffs are discussed and recommendations are given on the design of MEMBRANE networks and promising future research directions (chapter 4).

2 MEMBRANE approach

2.1 MEMBRANE scenarios and system concept assumptions

The initial objective of MEMBRANE was to define and parameterize the basic scenarios on which subsequent studies would be focused. This working framework was established taking into account both the project's goals and vision and the analysis of the need for the proposed technology, both from the community and the market point of view.

MEMBRANE's proposal addresses an alternative solution to meet the backhaul requirements in a wireless network deployment aiming at coverage or capacity enhancements, so unveiling if there is room for it is a decisive matter. Such analysis is also useful to depict the generic scenarios where MEMBRANE concept could offer an evident improvement (measurable socially, economically and technically), and so set up the framework for technological development.

Once target scenarios have been established, a detailed technical description is required, so that a number of parameters be defined and assessed. This parameterization should be based on the resources available on each research workpackage (namely WP3, WP4 and WP5), in order to make sure that all WPs are lined up and interactions are feasible.

2.1.1 The need for MEMBRANE technology

During the last years, one of the main concerns of EU governments has been to bridge the so-called ‘digital divide’, which reflects the differences in the performance experience when accessing broadband services in the urban and rural worlds. Both wired (DSL, cable, fibre) and wireless (2G, 3G, WiFi) network infrastructure has been traditionally mostly deployed in urban and suburban environments, but the take-up in rural areas is still fragmented.

2.1.1.1 Rural areas

There are millions of potential rural users in Europe that cannot access high bit rate services, and deploying broadband networks in rural areas could be a great opportunity to boost their economical and social development.

Two main problems can be identified in rural areas: insufficient broadband coverage (due to lack of investment, technical issues, unattractive business plan…) and limited capacity (which may affect service provision during seasonal inhabitants increase).

Both could be easily tackled if wireless backhaul networks are presented as economically and technically feasible solutions to provide broadband access anywhere, no matter how remote or isolated the target area is.

2.1.1.2 Urban areas

Different needs are foreseen in urban areas, where access networks are mostly available. The development of dozens of new capacity-consuming services, makes the quick deployment of high-speed ubiquitous networks imperative.

In addition, urban users are getting more and more addicted to being permanently on-line: e-mail, blogging, social networking are only a few examples of services that are being demanded anywhere, anytime. Ubiquitous mobile web is no more an idea, but a need.

Here, wireless backhaul solutions could play a major role, allowing a fast and economic deployment of any access network, such as clusters of WiFi access points at office buildings, or sets of domestic 3G/HSPA femtocells at households. Business models should be revised when wireless backhaul is available.

2.1.2 Frequency allocation

One of the main important parameters to be defined before developing MEMBRANE algorithms, simulator and prototype is the frequency band in which the whole system will work. To this end, information about candidate bands has been collected and analysed.

In the first place, it would be desirable to find a worldwide free frequency band, so that the cost of future MEMBRANE nodes could be reduced (simpler RF boards, economy of scale…). Unfortunately, most promising frequencies for wireless broadband systems are not fully available around the globe. Having this in mind, two frequencies have been identified as good candidates for MEMBRANE systems:

- 3.5 GHz: Up to 300MHz of bandwidth widely available in Europe and other regions. Propagation features at this frequency are quite good, allowing a wide coverage with a reduced number of nodes.
- 5 GHz: About 600 MHz of available bandwidth, divided in three “channels” with different requirements. It is characterised by higher propagation losses with respect to the 3.5 GHz band. Unusable in some EU countries for outdoor services.

2.1.3 MEMBRANE target scenarios

The fact that the needs for broadband access are different in the rural and urban worlds, led to the definition of two different target scenarios for the forthcoming MEMBRANE studies. These scenarios have been described using a large set of parameters that were classified in several groups, according to their relevance to different communication system layers and studies focus (e.g. link level, system level etc). In this way, research WPs could build their frameworks using only the parameter groups relevant to them.

2.1.3.1 Scenario 1: Rural

Scenario 1 is addressing rural remote areas, with sparse population, and distant from urban centres and main communication lines (motorways, railways, harbours). In these areas, the deployment of wideband services (both wired and wireless) is scarce due to economic and logistic reasons, but there are a number of potential users demanding the same service level than in other areas. These areas are usually covered by 2G and 2.5G nodes (both common and extended-range macrocells), and occasionally with the help of repeaters when the propagation conditions are unfavourable.

Some technical parameters that describe this outdoor scenario are:

- WINNER and SCM propagation models.
- Omni or multisectorial nodes with 1 to 8 antennas.
- Low number of access and intermediate nodes.
- User service mix shared among voice and non real time data.

Further details can be found in [MEM D2.1].

2.1.3.2 Scenario 2: Urban

Scenario 2 covers urban environments, ranging from business centres to residential neighbourhoods. So, this scenario should gather the features of both:

Business: Including office buildings, business centres, warehouses, factories, industrial premises and so. Wired wideband services are usually available in this kind of areas, and also wireless systems are frequent in office environments: 2G to 3G micro- and picocells, WiFi access points, etc.

Residential: Located in urban or suburban areas, these areas are usually covered in 2G to 3G systems by macro and microcells. There is also a growing interest from the operators' side to solve indoor coverage problems using femtocells. Besides, the growing demand for broadband internet access at home has lead to the presence of a great amount of WiFi access points in residential environments, so in this scenario we will have to cope with the simultaneous presence of all these kinds of nodes.

Some technical parameters that describe this outdoor scenario are:

- WINNER propagation models.
- Multisectorial nodes with 1 to 8 antennas.
- High number of access and intermediate nodes.
- User service mix shared among voice, real time and non real time data.

Further details can be found in [MEM D2.1].

2.1.4 Latest developments

The studies on target scenarios within MEMBRANE were carried out two years ago. Since then, in the broadband world some things have changed and some have not. These changes have not affected the basic assumptions of the analysis or its conclusions. However, it is worth presenting a brief summary of last years' developments:

Wired access: In urban areas, the presence of ADSL and ADSL+ lines has prevailed, turning dial-up or ISDN connections almost inexistent. Cable networks offer also competitive data rates, and fibre optics solutions (FTTH) have started to take off. In rural environments, the situation is not so optimistic, and even ADSL connections are not so common.

Cellular networks: The deployment of 3G networks can be considered almost complete, with reasonable coverage even in rural areas. Urban areas are beginning to take advance of recently deployed HSDPA and HSUPA services, which dramatically enhance the mobile web browsing experience. Besides, a first version of future LTE standards has been released, opening the way towards a fourth generation of mobile networks, with noticeably higher capacity demands and backhauling requirements.

Wireless access: Along with ADSL roll out, residential and business WiFi access points have proliferated. Also, a large number of towns and cities have begun to deploy freely accessible WiFi networks, allowing citizens to be connected inside the boundaries of the city. On the other hand, the expectations on WiMAX networks have not yet been fulfilled: the number of this kind of networks that have been deployed is quite limited, wide area coverage has not yet been achieved and there are only a small amount of WiMAX-capable terminals.

2.1.5 Conclusions

The work carried out within the scope of scenarios identification and market trends (MEMBRANE WP2) has successfully performed a comprehensive analysis of the users' and operators' needs for wireless mesh backhaul solutions. The requirement of providing broadband services in rural areas and enhancing current networks in urban environments will boost the development of technologies aiming to deploy wideband services in a fast, efficient and economical way.

This analysis has led to the characterisation of two typical scenarios that will be targeted by simulation platforms and prototype testbeds in order to assess the feasibility of the MEMBRANE concept.

2.2 Technical objectives

As discussed in the previous section the ongoing proliferation of wireless broadband data services is expected to lead to increased requirements for the backhaul network. The typical upgrade of wired lines to high-speed fibre networks may not always be an available or economically attractive solution. In such cases, wireless alternatives could offer an appealing alternative. MEMBRANE proposes to study the design of efficient wireless backhaul networks that meet the Quality of Service (QoS) demands of high speed access wireless networks, thus providing a technology shortcut that will help satisfy the social need for broadband data anytime anywhere in a much more expeditious way.

More specifically, the proposed work is especially targeted to cases where the wired infrastructure is either unavailable or too costly to upgrade. Some example scenarios include clusters of access points (e.g. 802.11), small cells and remote/isolated areas.

Given the need for an efficient wireless backhaul network, its successful deployment necessitates careful design and this is likely to require a number of technological breakthroughs. The main envisioned requirements of such a backhaul network are:

- Quality of Service in terms of throughput maximisation, delay reduction, coverage extension and overall capacity improvements.
- Reconfigurability with respect to network topology, traffic flow and propagation conditions.
- Heterogeneity and openness: Ideally, the backhaul should work in an agnostic way with respect to the employed access technology.
- Ubiquity with respect to making broadband services available equally fast to all areas.

In view of these requirements, the MEMBRANE workplan was organised around the following main technical objectives:

1. Multi-antenna multihop wireless backhaul problem definition and scenarios specification in terms of network topology, cell size and layout, access technology, propagation environment, antenna heights and configurations, performance evaluation methodology and critical performance metrics;
2. Theoretical multihop network performance analysis to assess the fundamental performance limits of multihop (MIMO) relay networks. Based on the understanding of these fundamental performance limits, design guidelines for protocols, such as routing and scheduling, and multiple antenna signalling are to be provided;
3. Development of novel multi-antenna link signalling and routing algorithms, for different propagation scenarios, antenna configurations and LOS conditions and multi-antenna-enabled scheduling and routing schemes, which exploit the spatial dimension and are reconfigurable with respect to traffic conditions and QoS constraints;
4. Development of novel routing, scheduling and power control algorithms for wireless backhaul network optimisation by taking full advantage of favourable channel conditions and avoiding co-channel interference;

5. Adaptation and optimization of the existing Transmission Control Protocol (TCP) algorithms to the MEMBRANE wireless multi-hop backhaul network;
6. End-to-end performance measurements and optimization of MEMBRANE network parameters by means of an integrated L1-L2-L3-L4 simulator comprising the new MEMBRANE scheduling (L2) and routing (L3) algorithms, the optimized transport layer and a suitable abstraction of the MEMBRANE PHY layer;
7. Development of the MEMBRANE System Simulation Software Platform in order to evaluate the link and system level performance gains achieved by the proposed multi-element scheduling and routing algorithms for wireless multihop backhaul IP network optimisation;
8. Development of the MEMBRANE Hardware Prototype in order to provide a proof-of-concept testbed for evaluation of the gains achieved by the proposed multi-element scheduling and routing algorithms for wireless multihop backhaul IP network optimisation;
9. Overall assessment of the proposed MEMBRANE approach and evaluation of design trade-offs involved in the development and implementation of multi-element multihop wireless backhaul networking;
10. Dissemination of the MEMBRANE findings to the international community through publications of results in the ICT concertation events, international conferences, seminars and workshops in the fields of signal processing and wireless communications;
11. Exploitation of the MEMBRANE findings by providing recommendations describing the MEMBRANE approach benefit to the operators and service providers and contributions to standardization organizations and research fora.

2.3 The MEMBRANE approach

In order to address the technical objectives discussed in the previous section, the MEMBRANE approach, studies and resulting innovation span the fields of physical layer and wireless technology, networking techniques and cross-layer optimisation.

System concept: In order to provide cost-efficient wireless mesh backhaul with low deployment costs and flexible provisioning, the MEMBRANE approach relies on a mesh networking multihop multi-antenna design that makes use of channel state information and interference optimised resource allocation and routing. The MEMBRANE system design provides higher speed backhaul, capitalizing on emerging trends, such as the evolving IEEE 802.16m standard, and allowing affordable availability of broadband access in rural areas or in countries with limited existing wireline infrastructure.

Physical layer: In order to meet distance, aggregate rate, and physical mounting requirements (e.g. non-line of sight) at the backhaul, multiple antenna techniques are deployed, both for the rural (‘macrocell’) and urban (‘micro/picocell’) scenarios. Through its combination of multiple hops and MIMO technology, the MEMBRANE approach sets itself apart from legacy (microwave-type) wireless backhaul solutions which require line of sight, high towers and fine tuning to operate properly and can easily fail if any of these conditions are not met.

Networking: For a given network layout, the MEMBRANE approach optimises the design of the topology of the backhaul network in terms of load, delay and resiliency by taking into account channel and interference conditions in order to provide adaptive scheduling, routing and power control. The joint design of intelligent/opportunistic scheduling and routing enhanced via the spatial dimension through intelligent antennas is a novel approach that can lead to unprecedented network throughput gains and QoS performance.

Cross-layer awareness: In order to meet stringent delay and throughput requirements in the face of changing wireless channel conditions and backhaul traffic load, channel state information and delay information have been exploited for optimal scheduling and routing. The transport, routing and scheduling algorithms design has been addressed in a cross-layer fashion, so as to increase performance and minimize interference between links activated simultaneously.

3 Major results, innovation and impact

3.1 Fundamental performance limits of multi-hop (MIMO) relay networks

The objectives of the study of the fundamental performance limits of multi-hop (MIMO) relay networks is to provide a framework for evaluating protocols (routing and scheduling) from an induced network (i.e. physical network in combination with protocol) capacity point-of-view.

Our results on performance limits of wireless networks come in two main types: asymptotic analysis in network size and asymptotic analysis in signal-to-noise ratio. Using these analysis tools, we derive the theoretical network capacity and the fundamental trade-off between rate and reliability in wireless relay networks. In the following, we first describe the system model considered and then briefly summarize our key findings. Our analyses lead to system design principles in both cases.

3.1.1 Asymptotic Results in Network Size

We analyze fading interference relay networks where M single-antenna source-destination terminal pairs communicate concurrently and in the same frequency band through a set of K single-antenna relays using half-duplex two-hop relaying. We assume that relays have channel state information (CSI), perform matched-filtering, and the destination terminals cannot cooperate. The main contributions are:

- We consider two different protocols, P1 introduced (for the finite-M case) in [Dan06] and P2 introduced in [Bol06]. P1 relies on the idea of relay partitioning and requires each relay terminal to know one backward (source to relay) and one forward (relay to destination) fading coefficient only. P2 does not use relay partitioning and requires each relay terminal to know all M backward and all M forward fading coefficients. We prove that in the large-M limit, provided the number of relay terminals grows fast enough as a function of M, under both protocols, the network "decouples" in the sense that the individual source-destination terminal pair capacities are strictly positive. The corresponding minimum rates of growth are shown to be K=M^3 for P1 and K=M^2 for P2. The protocols P1 and P2 are thus found to trade off CSI at the relays for the required (for the network to decouple) rate of growth of relays.
- We show that the growth rates K=M^3 for P1 and K=M^2 for P2 are sufficient to not only make the network decouple, but to also lead to the individual source-destination fading links **converge to non-fading links**. We say that the network "crystallizes" as it breaks up into a set of isolated "wires in the air". A large-deviations analysis is performed to characterize the "crystallization" rate, i.e., the rate (as a function of M, K) at which the decoupled links converge to non-fading links. In the course of this analysis, we develop a **new technique** for characterizing the large-deviations behaviour of certain sums of dependent random variables.
- For P1 and P2, we establish the impact of cooperation at the relay level on network capacity scaling. More specifically, it is shown that, asymptotically in M and K, cooperation in groups of L relays (which can also be interpreted as having multi-antenna relays in MEMBRANE settings) leads to an L-fold reduction in the total number of relays needed to achieve a given per source-destination terminal pair capacity.

3.1.2 Asymptotic Results in Signal-to-Noise Ratio

We analyze fading relay networks, where a source-destination terminal pair communicates through a set of half-duplex single-antenna relays using four time-division-multiple-access (TDMA) based protocols with linear processing at the relay level. For each protocol, we derive the diversity-multiplexing (DM) trade-off curve, and the sufficient conditions on the set of linear processing schemes and codebooks for achieving the DM-trade-off curve. We show that these conditions are independent of the underlying fading distribution, and guarantee the achievability of the DM-trade-off curve for any fading distribution. Our results show that the protocol with the highest degree of broadcasting and receive collision dominates the other protocols in terms of the DM-trade-off performance. Further, we demonstrate that delay diversity and phase-rolling at the relay level are optimal with respect to the entire DM-trade-off curve for each protocol, provided the family of codebooks, the delays and the modulation frequencies are chosen appropriately.

Our contributions can be summarized as follows:

- We introduce a **broad family of relay transmit diversity schemes** encompassing delay diversity and phase-rolling as special cases. Unlike prior work [Raj06, Rao07], we do not restrict relays to use unitary transformations.
- While the (numerical) and the (analytical) results in the literature are for the case of fixed rate (i.e., the rate does not scale with SNR), we provide a sufficient condition on the family of relay transmit diversity schemes introduced in this paper to achieve the entire DM-trade-off curve as defined in [Zhe03]. DM-trade-off curves for various protocols are derived using a novel technique that is used to calculate DM-tradeoffs in selective fading channels [Cor07] and a set of methods that we describe in the deliverables. The novelty of the methods we use arises from their **decreased dependence on the probability distribution** of the underlying fading coefficients.
- While the previous works in the literature require either orthogonality between the relay transmissions [Aza05] or unitary transformations at relays [Rao07] to achieve optimal DM-trade-off, we show that neither orthogonality nor unitary relay transformations is required for achieving DM-trade-off optimality (see Figure 1).
- While the previous works in the literature are concerned with the special case of Rayleigh fading [Raj06, Rao07, Aza05], our results are valid for a **general class of fading distributions**. Finally, we establish the **approximately universal code design criterion** for the half duplex relay channel for any fading distribution.

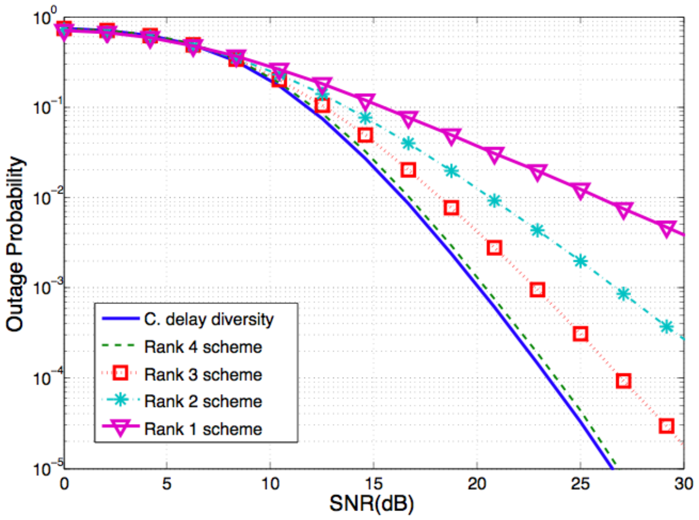


Figure 1– Simulation of different relaying schemes. Schemes proposed for MEMBRANE are depicted in blue and green respectively. Note that the asymptotic slopes of these curves are lower than that of existing schemes meaning that the outage probability decays much faster in increasing SNR for the MEMBRANE schemes.

3.2 Multi-antenna link signalling and routing

The design of suitable multi-antenna techniques for highly performing wireless mesh backhaul network was addressed in this part of the work (workpackage 4.1). A number of critical parameters /approaches were considered /assessed in this study:

(1) the impact of the estimation error on different space-time approaches

(2) the impact of cross-layer optimization techniques where routing and physical layer algorithms are jointly designed

(3) the impact of interference and the value of properly designed cancellation techniques at the receiver side

(4) the impact of propagation scenarios

(5) the impact of relay-aided transmissions.

First, we investigated the impact of channel estimation errors on various single link transmission schemes using a complex Gaussian error model. We compare the performance of the Alamouti scheme with the spatial multiplexing transmission for a system using 2 transmit antennas. For the system equipped with 4 transmit antennas, the performances of the hybrid scheme and spatial multiplexing are compared (see [MEM D4.1.2]).

A novel concept for high throughput relay transmissions was then proposed with multiple antennas. Differently from previous proposed schemes where independent streams are directly sent to the destination or sent to the relay and then forwarded to the destination, we ‘route’ the independent streams to different relays and at the same time send directly to the destination in order to maximize the system throughput. This approach, called **data splitting**, is particularly appealing for correlated channels, where the spatial multiplexing gain cannot be fully obtained by sending the data via only one relay node. An implementation of this concept based on spatial decomposition and on a joint uplink/downlink iterative optimization is also proposed.

We then considered a rural area scenario where cellular setup is deployed, and study a two-hop relay system where only two relay nodes are available. We study the performance of two-path relaying protocol using multiple antennas. The interference between two relay nodes is either treated as noise, or cancelled at the relay node using zero-forcing technique. The capacity for the system using two-path relaying can be further increased by optimally switching between the above two methods (see [MEM D4.2.1]).

Finally, we addressed the problem of designing interference cancellation schemes in an unsynchronized wireless backhaul network. Different non-stationary algorithms are proposed based on the second- and higher-order statistics.

3.2.1 High data rate relay transmissions using multiple antennas

In order to provide a highly performing and cost-efficient solution for wireless backhaul applications, a novel concept was proposed based on an adaptive, multihop (mesh) networking design that makes use of channel state information for advanced Multiple Input Multiple Output (MIMO) processing, spatial and relaying gains combination and cross-layer optimized resource allocation and routing.

The basic idea is to split the main data stream into multiple independent spatial sub-streams and send it to a number of relays, during the first hop, and then to successfully collect them at the destination, during the second hop. The relays selection -out of all available relays- is based on an opportunistic approach: an available spatial mode is allocated to a given relay only if it involves a sum-rate improvement. Due to this "relay diversity" effect, the overall throughput grows as a function of the number of candidate relays.

As explained in [MEM D4.2.1] and illustrated in Figure 2, the Data Splitting Algorithm (DSA) divides the relay transmission in two ‘phases’ corresponding to each one of the to hops and optimizes transmission during the first hop (‘virtual downlink’) based on the principle of Multi-user Eigenmode Transmission (MET) originally proposed for downlink multiuser MIMO transmissions and extended here to the multiple relay case. During the second hop (‘virtual uplink’), the processing of signals from different relays at the destination is based on the uplink equivalent of the MET scheme.

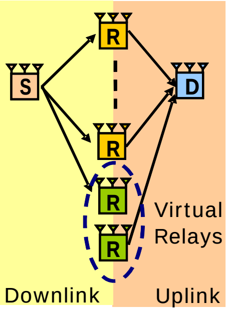


Figure 2– The Data Splitting Algorithm concept

The link level performance of DSA was investigated in [MEM D4.2.1],[Boc07] under two different power constraints: a sum power constraint (SPC) over all relays and independent power constraints (IPC) on each relay (see example in Figure 3). One could further argue that a SPC is a reasonable assumption when power consumption and energy efficiency are of importance in a certain deployment, as it may be in the case of user-owned access point serving as candidate relay nodes, whereas this may not be the case in a wireless backhaul network consisting of fixed node topology (deployed by the operator), and there IPC may be a reasonable assumption.

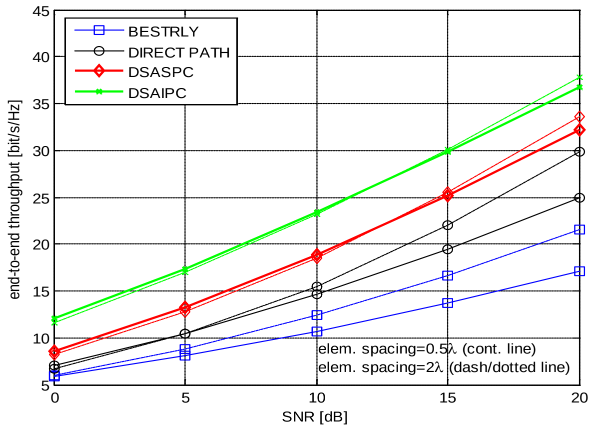


Figure 3– Performance comparison between the proposed DSA algorithm, best relay selection scheme and direct link transmission. Each node has 8 antennas with inter-element spacing of 0.5 λ (continuous line) and 2 λ (dash/dotted line). A WINNER B1 propagation scenario has been considered with LOS.

The performance of DSA was assessed at the system level (also in the framework of workpackage 5.1 on system simulations). It was shown that DSA-SPC provides over 30% average node throughput improvements as compared to the Direct Link transmission (no relaying) baseline and 15% improvements over the Hard Switching between Direct Link and Best Relay, whereas in terms of outage (10% probability) node throughput, Hard Switching and DSA outperform Direct Link by a factor of 3 and 4 respectively (see [Ale08]).

3.2.2 Two-path Relaying using Multiple Antennas

In this part of the work we focus on the rural scenario. We consider two-hop transmission and assume no direct link between non-neighbouring cells. Hence the source node needs to communicate with the destination node via two relay nodes. We also assume that all the other neighbouring cells are too far away from the destination and therefore they cannot be used as relays in this two-hop network.

The two-path relaying protocol recently been proposed in [Ran07][Fan06] to improve the spectral efficiency of the relay network works as follows:

(1) In the first time slot, the source node S transmits data stream 1 to relay node R1.

(2) In the second time slot, S transmits data stream 2 to R2, and R1 forwards data stream 1 to D. Note that during this process, the transmission between R1 and D interferes the transmission between S and R2.

(3) In the third time slot, S transmits data stream 3 to R1, and R2 forwards data stream 2 to D. The transmission between R2 and D interferes with the transmission between S and R1.

The above procedure (2) and (3) goes on continuously during the rest time slots. Assuming that there are M time slots used for transmission, the multiplexing ratio for this algorithm is (M-1)/M. The main problem though for this two-path relaying protocol is the interference incoming when the source transmits to one relay, while at the mean time the other relay forwards the data to the destination.

In our studies we consider the case when multiple antennas are deployed in all nodes. Two transmission schemes are studied:

- The first one treats the interference as noise at the relay nodes, along the lines of the works done by [Ran07][Fan06], but with multiple antennas.
- The second algorithm uses the antenna arrays at the relay side to cancel the interference from the other transmission.

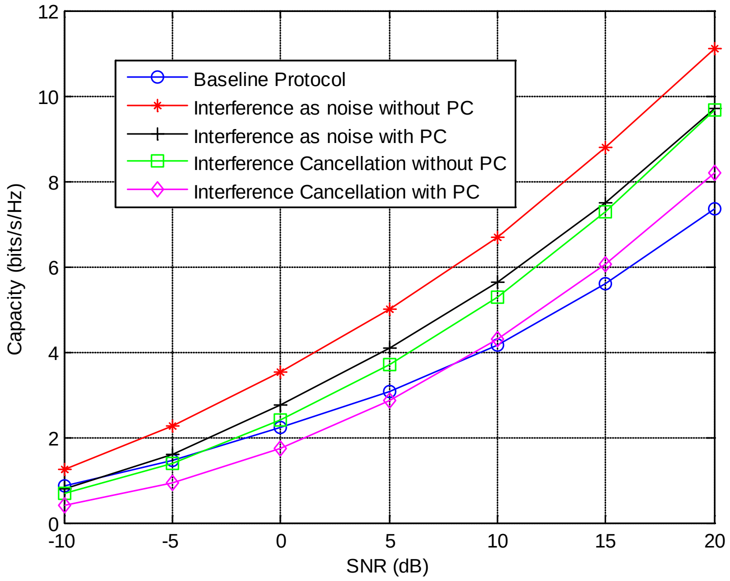


Figure 4– Simulations of two-path relaying protocols using 4 antennas in each node in rural LOS scenario, the distance between neighboring antenna elements is 0.5λ (The baseline refers to the protocol presented in [Nab04]).

It was shown in [MEM D4.1.2] that for specific channel realizations, either the two-path relaying with or without interference cancellation may be favoured. To further improve performance it was proposed in [MEM D4.1.2] to optimally switch between two different two-path relay transmission schemes.

3.2.3 Interference Cancellation at the receiver for unsynchronized backhaul networks

We addressed the problem of designing interference cancellation schemes in WiMAX-based unsynchronized backhaul networks. Novel second- and higher-order statistic non-stationary algorithms have been proposed to this end (see [MEM D4.1.2] and references therein). Their efficiency has been studied by means of comparison to the conventional stationary training based LS solution as well as to the developed non-asymptotic ML-based benchmark. The OFDM versions of the developed algorithms have been studied in the typical scenarios taking into account particular locations of backhaul network nodes and typical propagation conditions in the urban and rural areas.

It has been demonstrated that the proposed non-stationary techniques significantly, up to 3-5 times, outperform the conventional Least-Square estimator in the typical B1/LOS/NLOS and D1/LOS scenarios.

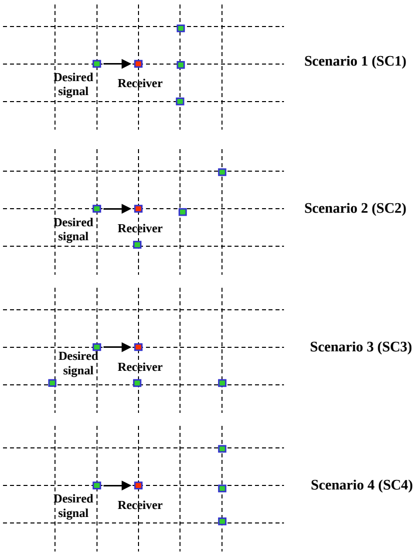


Figure 5– Simulation scenarios SC1-SC4 for interference cancellation studies

The studies performed indicated that in difficult interference scenarios (see Figure 5) such as SC1 and SC2 the non-stationary Semi-Blind algorithms, especially the Symbol by Symbol Reconfigurable Finite Alphabet (SSRFA) algorithm significantly outperforms the conventional training-based Least-Square estimator. In simple scenarios with low number of dominant interference components, all the considered algorithms demonstrated similar results.

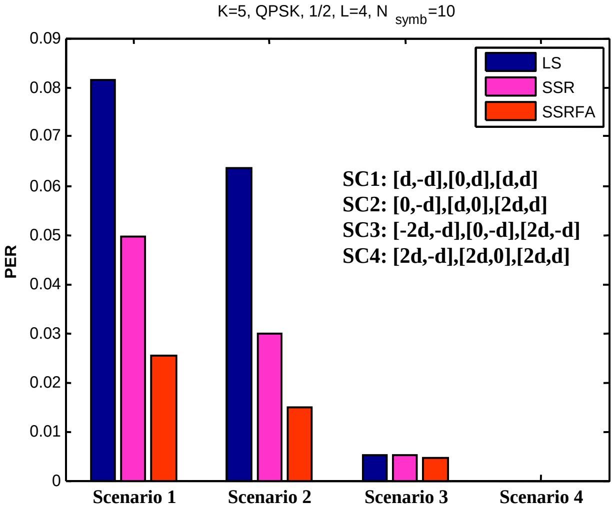


Figure 6– PER performance for B1/NLOS with 2λ antenna and $d = 200$ m grid spacing for fixed CCI positions SC1-SC4

3.3 Routing, scheduling and power control for wireless backhaul network optimisation

The aim of the studies on routing, scheduling and power control is to design and analyse radio resource management algorithms at the MAC level; antenna-aided jointly optimized opportunistic routing and scheduling algorithms, as well as power control policies for efficient resource utilization for the considered MEMBRANE wireless mesh networks. The main innovations, achievements and most important results are summarized in the following.

3.3.1 A generic framework of distributed scheduling in wireless mesh networks

Wireless multi-hop, mesh networks are being considered as a candidate to backhaul data traffic from access networks to the wired Internet. To enhance system performance, scheduling algorithms for wireless mesh networks are desirable to take advantage of multi-user diversity resulted from time-varying channel condition and space-varying path loss. Although many existing scheduling algorithms or medium access protocols have been adopted for the wireless mesh networks, they do not perform well, given that the algorithms are devised for wireless access. During the MEMBRANE project, we studied the computational complexity in finding the optimal schedule for a mesh network with time-division-duplexing (TDD) operations and showed that the complexity of optimal scheduling for mesh networks is at least NP-complete. Therefore, we proposed a novel heuristic 3-step distributed scheduling framework for wireless mesh networks with open definitions of utility function [Hou08][Hou07][Hou7b][Hou06][Hou]. The sketch of the algorithm is as follows.

1. To exchange the link utility with the neighbouring routers.
2. To make an initial decision, e.g. to find a link which is with a good utility and a small prior probability to collide with neighbours' decision.
3. To exchange the initial decisions with neighbours and finalize the scheduling by dropping the conflicting initial decisions.

Complexity analysis shows that our proposed framework is of polynomial-time complexity. Mathematical analysis of the efficiency of our scheduling framework shows that in terms of average number of concurrent active links in the mesh network, our scheduling algorithms, with 1-hop and 2-hop neighbour information respectively, can achieve 59% and 73% compared with the upper bound performance. Simulation results compare our framework with the tree-structural approach and reveal that our proposed framework is highly capable of selecting and scheduling links with high utility in a fully distributed manner. Furthermore, by comparing with the centralized ideal scheduling algorithm, which is NP-hard to realize, simulation results show that our 1-round and 2-round opportunistic scheduling frameworks can achieve 80% and 69.5%, respectively, of the optimum in terms of aggregated utility. Moreover, in terms of interference, we show that our framework maintains strong temporal correlation of interference, which is required to ensure proper channel predictions for scheduling gain and for distributed power control [Hou06].

3.3.2 Cross-layer performance of the mesh scheduling with various physical layer techniques

Although multiple-antenna techniques have been extensively studied in the literature, not much research for multiple antennas has been received in the backhaul context. During the 2nd year of MEMBRANE project, we investigated the cross-layer performance between various multiple-antenna techniques and backhaul schedulers using physical layer abstraction [Hou08]. A cross-layer study composed of the physical layer abstraction and the scheduler simulation reveals that with interference eliminating MIMO techniques, the 2-round scheduler can mitigate the greater interference due to the greater link density, and further enhance the network throughput by 30% over the 1-round scheduler. Furthermore, simulation results unfold that the beamforming (dominant-eigenmode-transmission) and interference cancellation (least-square-interference-cancellation) schemes are optimized for noise-limited and interference-limited scenarios, respectively (Figure 7).

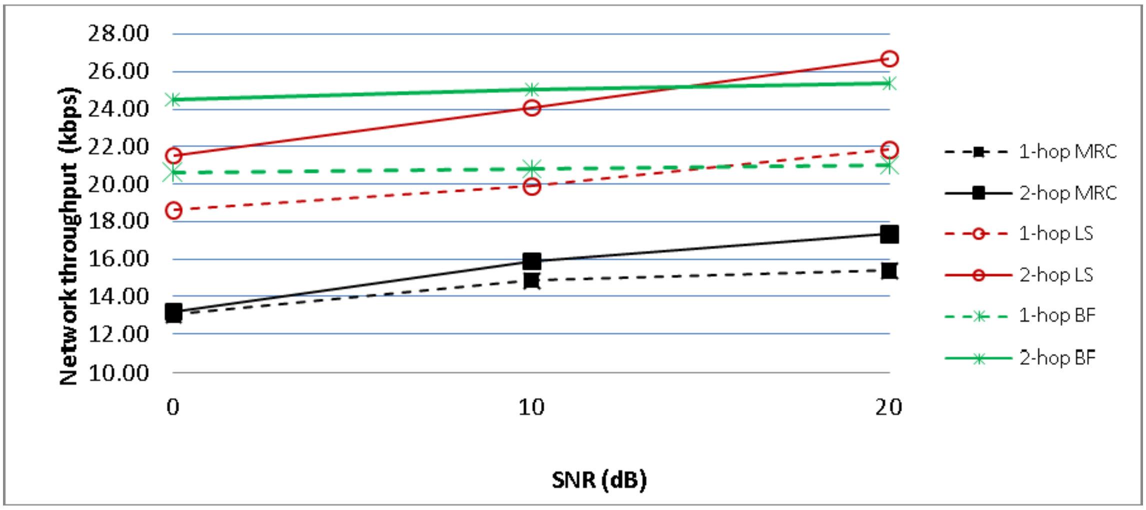


Figure 7– Comparison in terms of network throughput among different PHY techniques with varying SNR

3.3.3 A new QoS utility function for mesh scheduling algorithms

To ensure QoS, the routing algorithm in use has to reserve and allocate radio resources for various competing data flows during selecting appropriate routes for them. Such resource allocation must be enforced by the scheduling algorithm. Otherwise, the QoS promised by the routing protocol to its applications cannot be guaranteed. Towards this end, we proposed a novel scheduling utility definition for wireless backhaul networks [Hou07]. It is shown by analysis and simulation that in a long run the scheduling algorithm, as governed by the scheduling utility, converges to the desired throughput allocation, which can be specified by the routing protocol in use to guarantee quality of service. The novel scheduling utility definition has been filed as a UK patent in Nov 2007.

3.3.4 Impact of erroneous channel info on scheduling

Current and next-generation wireless networks take advantage of scheduling techniques such as the Proportional-Fair (PF) algorithm to achieve multi-user diversity over time-varying wireless channels and thus high system throughput. Therefore, the first part of the work examines how inaccurate channel-quality predictions can lead to significant performance degradation of the packet scheduler. We demonstrated and quantified how the inaccuracy of predicted data rates in future time slots for various users can significantly degrade the performance of the PF scheduling in wireless networks. We proposed to enhance the scheduling algorithm by using an appropriate algorithm to improve the accuracy of the data-rate predictions. In particular, the Wiener filtering technique can be applied to accurately predict data rates for Rayleigh fading channels. Our simulation results reveal that relatively to the commonly used extrapolation and exponential-smoothing methods, the channel predictions by the Wiener filter noticeably improves the PF scheduler’s performance in terms of users’ received SNR, error rate and packet delay.

3.3.5 Performance Analysis of Proportional Fair Scheduling

This research provides a theoretical framework to facilitate the research on proportional fair scheduling (PFS).

PFS provides good balance between throughput and fairness via *multi-user diversity* and *game-theoretic equilibrium*. Very little analytical work exists on understanding the performance of PFS.

All existing results are obtained with the assumption that there is some kind of independent identically distributed (*i.i.d*) relationship among users, and most results are for cellular networks with *Rayleigh* flat-fading. In this research, we develop an analytical framework for the *PFS* algorithm that applies to general flat-fading environments [Liu08a][Liu08b][Liu08c][Liu08d][Liu08e]. Moreover, existing analytic results can be directly derived by using the proposed framework in corresponding scenarios.

For the framework to be complete, we first consider PFS in cellular networks. By mathematically rigorous analysis, we obtain the upper and lower bounds for both the average throughput of a user and the probability it is scheduled. The results reveal that the average throughput of a user solely depends on its own channel statistics when its instantaneous data rate is *Gaussian*.

Next, PFS in wireless mesh networks is discussed. Specifically, we assume that orthogonal frequency-division multiplexing (*OFDM*) and single-input multi-output (*SIMO*) techniques are used in the mesh network.

Being mathematically graceful and simple, the analytical framework developed in this research is instrumental in optimizing the PFS-enable system performance and opens new vistas for studying the PFS algorithm in a *cross-layer* design context. To the best of our knowledge, this work is the first one theoretically investigating the PFS problem in general fading, cellular or multi-antenna *OFDM* mesh networks without the *i.i.d* assumption in literatures.

Compared to existing research on PFS, the innovations of our work are as follows:

1. rate model:
    a) All existing work use linear rate model or logarithmic rate model.
    b) We use accurate Gaussian approximation method to model capacity.
2. PF metric:
    a) Most existing work use modified version of PF metric to ease the analysis.
    b) We use original/un-modified PF metric in our analysis.
3. i.i.d assumption:
    a) Most existing works typically assume that there exists some kind of i.i.d relationship among users/nodes to facilitate the mathematical derivation.
    b) We do not have such limitation.
4. network model:
    a) All existing work applies to cellular networks only.
    b) Our results apply to cellular networks, and extend to wireless mesh.
5. fading channel:
    a) All existing work are for Rayleigh flat-fading cases.
    b) Our framework applies to general flat-fading cases, i.e., Rayleigh flat-fading, Rician flat-fading, and/or hybrid Rayleigh+Rican flat-fading scenarios.
6. antenna model:
    a) Most existing work are for the SISO antenna system
    b) Our results apply to both the SISO and the MIMO system.

Our main results can be summarized by the following theorems

Theorem 1: *In an N-user cellular network implementing the PFS algorithm, where the instantaneous data rate* R_j *of user j* ($j=1,2,\ldots N$) *is statistically independent random variable with probability density function* (*pdf*) $f_{Ri}(.)$ *and cumulative distribution function* (*cdf*) $F_{Ri}(.)$, *if the standard deviation* σ_{Rj} *of* R_j *is a monotonically increasing, concave function of its mean value* $E[R_j]$, *then the mean throughput* $E[\mu_j]$ *of user j has following upper and lower bounds,*

$$E[\mu_j] \le \sigma_{R_j}\int_{-M_j}^{\infty}\left(y\sigma_{R_j}+E[R_j]\right)f_{R_j}\left(y\sigma_{R_j}+E[R_j]\right)\times\left[\prod_{\forall i\neq j, E[R_i]\ge E[R_j]}^{N}F_{R_i}\left(y\frac{E[R_i]}{E[R_j]}\sigma_{R_j}+E[R_i]\right)\right] \\ \times\left[\prod_{\forall i\neq j, E[R_i]< E[R_j]}^{N}F_{R_i}\left(y\sigma_{R_i}+\frac{\sigma_{R_i}}{\sigma_{R_j}}E[R_j]\right)\right]dy \qquad (1)$$

$$E[\mu_j] \ge \sigma_{R_j}\int_{-M_j}^{\infty}\left(y\sigma_{R_j}+E[R_j]\right)f_{R_j}\left(y\sigma_{R_j}+E[R_j]\right)\times\left[\prod_{\forall i\neq j, E[R_i]\ge E[R_j]}^{N}F_{R_i}\left(y\sigma_{R_i}+\frac{\sigma_{R_i}}{\sigma_{R_j}}E[R_j]\right)\right] \\ \times\left[\prod_{\forall i\neq j, E[R_i]< E[R_j]}^{N}F_{R_i}\left(y\frac{E[R_i]}{E[R_j]}\sigma_{R_j}+E[R_i]\right)\right]dy \qquad (2)$$

where μ_j *is j's throughput,* $E[R_j]$, σ_{Rj} *are the mean and standard deviation of* R_j*, respectively.* $M_j=E[R_j]/\sigma_{Rj}$.

Theorem 2: *In an N-user cellular network implementing the PFS algorithm, if the instantaneous data rate of each user is statistically independent Gaussian, then the mean throughput of user j can be approximated by*

$$E[\mu_j] \approx \frac{E[R_j]}{N}\times\left(1-\left[F_{(0,1)}\left(-E[R_j]/\sigma_{R_j}\right)\right]^{N}\right)+\int_{-M_j}^{\infty} y\sigma_{R_j}\, f_{(0,1)}(y)\times\left[F_{(0,1)}(y)\right]^{N-1}dy \qquad (3)$$

and the average probability that user j is scheduled can be approximated by

$$\Pr\left(I_j=1\right)\approx\frac{1}{N}\times\left(1-\left[F_{(0,1)}\left(-E[R_j]/\sigma_{R_j}\right)\right]^{N}\right) \qquad (4)$$

where $f_{(0,1)}(.)$ *and* $F_{(0,1)}(.)$ *are the pdf and cdf of zero mean, unit variance standard normal distribution, respectively.*

Theorem 3: *In an N-node OFDM+SIMO+PFS full duplex mesh network, if the feasible data rate* $R_{i,j}$ *of the directed SIMO link between node* n_i *and its neighbour* n_i ($i, j=1,2,\ldots N$) *is statistically independent Gaussian, then the mean incoming and outgoing data rate of node* n_j *can be approximated by*

$$\begin{cases} E[\alpha_j]\approx\sum_{n_i\in\Omega_j}\left[\frac{E[R_{i,j}]}{N_j+1}+\int_{-M_{i,j}}^{\infty}y\sigma_{R_{i,j}}\,f_{(0,1)}(y)\left[F_{(0,1)}(y)\right]^{N_j}dy\right] \\ E[\beta_j]\approx\sum_{n_i\in\Phi_j}\left[\frac{E[R_{j,i}]}{N_i+1}+\int_{-M_{j,i}}^{\infty}y\sigma_{R_{j,i}}\,f_{(0,1)}(y)\left[F_{(0,1)}(y)\right]^{N_i}dy\right] \end{cases} \qquad (5)$$

where N_j *is the total number of neighbours that* n_j *can receive from,* $f_{(0,1)}(.)$ *and* $F_{(0,1)}(.)$ *are the pdf and cdf of standard normal distribution, respectively.*

3.3.6 Joint Scheduling and QoS Routing Framework

The MEMBRANE network is expected to support different types of applications with multiple and various quality-of-service (QoS) requirements. Existing works do not simultaneously integrate multiple QoS constraints in route discovery and maintenance phases while they overlook the interaction between medium access control (MAC) and routing algorithms. On the other hand the aforementioned distributed opportunistic proportional fair scheduling algorithm has been proven a promising technology enabler for the MEMBRANE network since it can take advantage of the multi-user diversity and the dynamic nature of the wireless channel. However, the main drawback of this scheme is that due to its opportunistic nature it cannot provide hard resource guarantees and therefore it is not easily applicable to networks with QoS requirements.

In order to exploit the advantages of the proposed scheduler while overcoming its inherent difficulties we provide a novel fully distributed, cross-layer scheme, comprising PHY, MAC and Network layer functionalities [Liu08f][Liu08g]. The main innovations of the proposed framework is that (1) it defines a unified approach to integrate multiple QoS constraints into a sole utility function, (2) it provides a novel utility metric as an interface between the routing and scheduling algorithm to successfully exploit the multiuser diversity gain.

In this way we are able to provide end-to-end QoS guarantees to applications that have multiple constraints (such as, throughput, delay, packet-error-rate, etc.) while at the same time we can optimise the overall network performance by exploiting the multi-user diversity gain and avoiding creating bottlenecks that can negatively affect the network connectivity. Our proposed framework is fully distributed, scalable to network size and has a low complexity. Extensive simulation studies show that our algorithm can successfully guarantee QoS while achieving better network performance, in terms of higher network goodput, end-to-end packet delay and QoS outage probability, compared to other standard techniques.

3.3.7 Connection Admission Control (CAC) and Grade of Service (GoS)

A further improvement of the proposed scheduling and QoS routing framework is the introduction of a Connection Admission Control scheme for different levels of QoS that allows us to manage more efficiently the available resources between the existing and new flows [Liu08h]. In this way we are able, not only to further improve the overall network performance by minimizing, but also to provide grade-of-service to the underlying applications. Our contribution is twofold:

(1) The connection admission control scheme is fully distributed and minimizes the negative effects of new flows on the existing ones (thus, minimizes the outage probability).

(2) The multi-level QoS resource management algorithm not only controls the QoS levels of the new flows but can also degrade the level of existing flows to release resources for new flows (thus, minimizes the blocking probability) while it guarantees the required GoS to the underlying applications.

Simulation analysis shows that the proposed scheme achieves higher throughput while it reduces the outage probability of the existing flows (Figure 8).

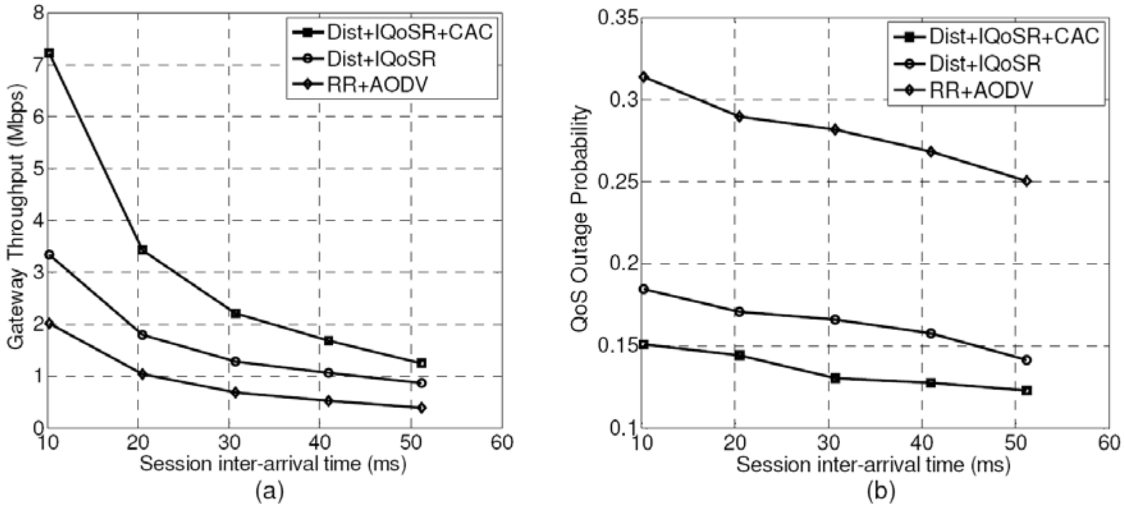


Figure 8– Simulation results on (a) Network throughput and (b) QoS outage probability per session value with respect to the new session inter-arrival time.

3.3.8 MIMO Routing with QoS Provisioning

While multiple antenna techniques have been widely analyzed for single link transmission scenarios or from the medium access control (MAC) perspective, their usage and impact on network layer and more specifically their interaction with routing has not received much research attention. In this framework, we investigated the interaction between multiple antenna techniques and routing. A novel routing scheme that exploits the multi-user gain capability of MIMO by controlling the number of ongoing transmission in order to increase the end-to-end throughput and guarantee the required quality-of-service (QoS) constraints has been presented and analyzed [Gke08].

The proposed novel QoS routing algorithm exploits some main MIMO properties such as multiplexing gain and interference cancellation, but also the benefits of a space-division-multiple-access (SDMA) scheme. In this way, we are able not only to increase the overall network throughput but also to optimally distribute the data traffic over the network topology in a way that we can guarantee the required long-term QoS throughput to the underlying applications. This becomes feasible by controlling the available degrees of freedom for each wireless MIMO transceiver so that it has enough resources to cancel out the interference generated by adjacent transmissions. In order to achieve this, the proposed scheme goes through the following steps:

1. Differentiate strong from weak interfering streams.
2. Control the number of strong interfering streams while treating the weak ones as Gaussian noise.
3. Estimate the expected link throughput without considering any interference.
4. Include a resource reservation margin ξ to account for the allowing interference.
5. Use a routing algorithm with a novel utility function to guarantee the end-to-end QoS throughput requirements for the whole duration of each data session.

Simulation results showed (Figure 9) that the proposed cross-layer framework can guarantee long-term QoS while at the same time significantly increases the overall network throughput as compared to the conventional orthogonal in space and time coordination.

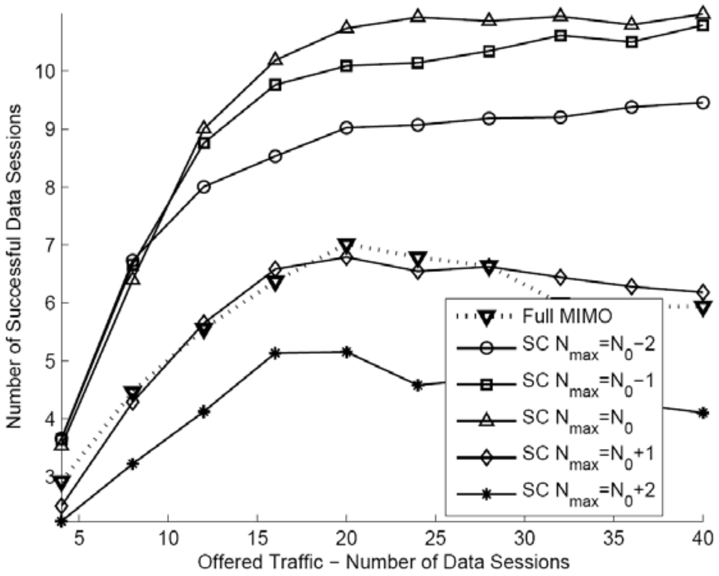


Figure 9– Number of successful QoS data sessions versus offered traffic for different values of the maximum number of allowed streams per receiver (Nmax), with and without stream control.

3.3.9 Power Control

Our work has focused on the development of a power control algorithm suitable for its integration with the rest of cross-layer routing and scheduling techniques defined throughout this work-package. This power control algorithm is expected to minimise the transmission power used by each MEMBRANE node, in order to optimise overall network interference, capacity and power consumption. To this end, game theory has been selected as a promising area to develop such algorithm. Game theory allows to model, analyse and manage scenarios where several users compete for a limited set of resources in a selfish way, but following a rational behaviour that, hence, is predictable. In addition, game theory allows the users to take the decisions on the usage of the resource, and so there is no need of a centralised management of the network. This approach is in line with the aforementioned decentralised resource allocation schemes that have been proposed for routing and scheduling.

The proposed power control scheme considers the selection of the optimal transmission power at each network node as a non-cooperative game. In every time slot, each node tries to maximize the value of a utility function that depends on the perceived goodput (and, therefore, on the SINR of the link), so that the entire network achieves a Nash equilibrium. This equilibrium point is not a Pareto-optimal one, and so further improvements are possible if some kind of cooperativeness is achieved among nodes. Two strategies are then explored, i.e., pricing techniques and repetitive games:

In pricing games, a price is imposed to each node for the amount of used power resources. Thus, the utility function should be modified to take this into account (See [MEM D4.2.2] section 5.3.4).

In repetitive games, the decisions taken by nodes affect the future values of the utility functions. A penalization is then applied each time a node transmits with excessive power (see [MEM D4.2.2] section 5.3.5).

Although repetitive approach leads to better (Pareto sense) balance points than pricing one, this last one has been selected for our algorithm, as it allows applying customized restrictions to each node, according to the expected QoS. In order for the nodes to evaluate their utility functions, they need to be aware of the attainable bit error rate of the links. So, channel quality indicators (CQI) should be periodically measured by the nodes and reported to their neighbours. Our proposal suggests sending CQI information every 0.5 ms, trying different approaches to reduce redundant data (see [MEM D4.2.2] section 5.3.6)

The algorithm has been further improved with the use of a penalty parameter that prevents low-utility links to be underemployed. So, when a link is used for transmitting data for several consecutive timeslots, its utility function is decreased for a number of slots, in order to keep the fairness of the system and avoid the monopolisation of the resources.

MATLAB simulations have been carried out to assess the performance of the different gaming techniques and compared with the centralised approach. Simulations show a 5 to 10 dB improvement in the averaged per node transmission power. The performance evaluation of the selected algorithm unveils that average throughput can be kept at previous values, while data transmission waiting time at each node is dramatically decreased due to the usage of penalty parameters.

3.4 Wireless multi-hop backhaul IP network design

One of the goals of the IP network design studies in the framework of MEMBRANE was to propose and analyse methods for optimizing existing TCP (Transmission Control Protocol) performance in the environment considered for the MEMBRANE project, which is reconfigurable multi-antenna, multi-hop wireless backhaul network.

TCP is the standard protocol for IP networks, independently from the type of MAC and physical layer of the considered network. As a consequence, the TCP protocol is used both in wired and wireless networks. TCP protocol was originally designed for wired networks, in which TCP assumes that BER (Bit Error Rate) is extremely low. For this reason, traditional TCP considers every occurring loss or timeout (in receiving acknowledgement) due to buffer overflows in the intermediate nodes. In the MEMBRANE wireless networks this assumption is not always true, because of many uncontrollable quality-affecting factors, such as weather conditions, urban obstacles, multipath interference, and large moving objects. Therefore, in a network with wireless links, which are characterized by a high BER, the packet losses are often caused by corruption due to link errors and not by congestion [Amir95], [Tian05]. As a consequence, TCP’s congestion control procedure will mistakenly and unnecessarily reduce the sending rate, causing a degradation of the network throughput, inefficiency of network resource utilization and continuing interruptions of data transmission.

The cross-layering approach has been chosen as an innovative point of view for improving TCP performance in MEMBRANE wireless networks: it exploits the MEMBRANE characteristic to be able to easily exchange information among different layers.

We identified essentially three possible types of cross-layering approach for TCP performance improvement:

- ECN (Explicit Congestion Notification), as specified in RFC 3168 [RFC 3168] and implemented in TCP Jersey [Li95]:: an intermediate node sets a bit in the IP header of the passing packets when its node buffer size has reached a certain threshold and it is going to be overloaded; when the packets reach the destination, destination TCP sends back a TCP ACK that notifies the source of the possible congestion event, therefore source TCP can reduce its transmission rate in order to avoid congestion.
- ELN (Explicit Loss Notification): MAC intermediate nodes, when receive a corrupted packet, mark it and forward it to the destination; destination TCP is therefore informed about each specific packet loss due to channel errors and is able to ask directly the retransmission of the specific packet to the source TCP, without rate reduction [Buc05].
- Notification of the available rate on the path: the intermediate nodes notify to the end nodes the bottleneck link throughput that is the minimum of all one-hop throughputs along the path, so that the TCP does not transmit more data than the amount the network can manage, therefore avoiding congestion. We call this new approach ERN, Explicit Rate Notification, and we developed it expressly for the MEMBRANE framework: since in MEMBRANE routing and scheduling layers exchange information about the instantaneous throughput that a link can offer, the proposed idea is to allow also TCP to know this information and use it for limiting its congestion window and therefore the amount of traffic injected in the network.

The optimality of the devised cross-layer approaches was tested with experimental simulations, by means of OPNET [OPNET] simulators.

Two different simulation suites have been developed. Analysis started in a simplified MEMBRANE network model and, in a second stage, the initial analysis have been improved, with the integration of the scheduling and routing approaches proposed within the MEMBRANE project. The developed integrated simulator is a complex simulation environment, and serves the other main goal of the IP studies within MEMBRANE, that is the evaluation of the performance of the overall MEMBRANE network, when all the innovative developed cross layering solutions are in place and work together: L2, L3 and L4 MEMBRANE protocols with a simplified version of MEMBRANE L1.

The integrated simulator was developed using the OPNET modeller application (Figure 10). A model for each layer of the TCP-IP stack, starting from the physical layer up to the application layer has been implemented. For the physical layer, we modified the standard radio channel of the OPNET simulator, introducing the small-scale fading and implementing the Jakes model (including Doppler frequency), in order to generate the wireless links between MEMBRANE nodes. A directional (steering) antenna model and an automatic positioning system have been developed in order to analyze the potential spatial reuse of MIMO systems. The MEMBRANE distributed opportunistic scheduling algorithm and the MEMBRANE QoS routing algorithm have been implemented and integrated. At the TCP layer, the discussed cross-layer approaches have been implemented. Finally, at the application layer, the application models of OPNET have been adopted, which allow to simulate standard FTP connections, voice, video and many other applications.

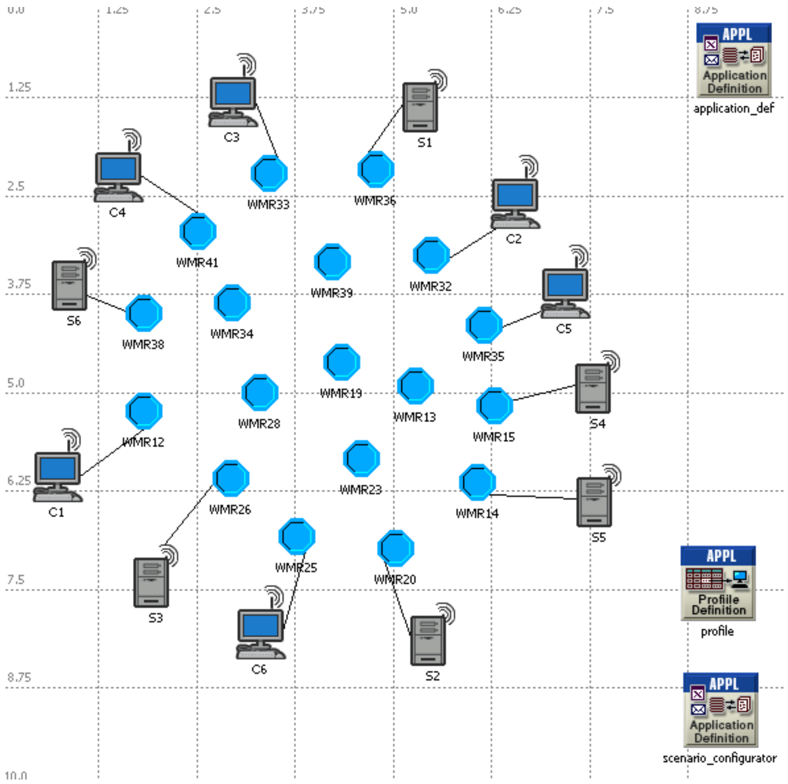


Figure 10– A typical OPNET scenario used for the simulation campaign.

The developed simulation environment can simulate any combination of applications traffic. Furthermore, numerous configuration parameters have been defined, allowing a great flexibility in the evaluation of the best parameters combination according to a specific application traffic bundle. With the integrated simulation environment it is possible to simulate a MEMBRANE network with any topology of nodes, in which different bundles of real applications can run, allowing performance evaluation and consequently the tuning of some network parameters to further improve network performance.

For TCP performance evaluation, we selected a set of simulation scenarios in which we simulated TCP congestion control algorithms and the above mentioned cross layering algorithms, in order to propose an optimized TCP protocol specific for the MEMBRANE network. Simulation results confirm that the Explicit Rate Notification algorithm gives the best performance in every of the tested scenarios over the other two considered cross-layer approaches and over other classical TCP protocols (Reno, New Reno [RFC 2582], Jersey). In the MEMBRANE network environment, characterized by average good PER (Packet Error Rate) values, a precise measure of the available throughput can improve significantly goodput (that is, the number of useful bits per unit of time forwarded by the network from a certain source node to a certain destination, excluding protocol overhead, and excluding retransmitted data packets), because it gives TCP a real time picture of the network status, in particular in those cases (high number of streams and high number of hops) in which the bandwidth resource is under contention.

See for example Figure 11 that shows obtained average connection goodput with respect to average PER for the case of six concurrent TCP flows in the network, each of which has an average of five hops between any client and server pair.

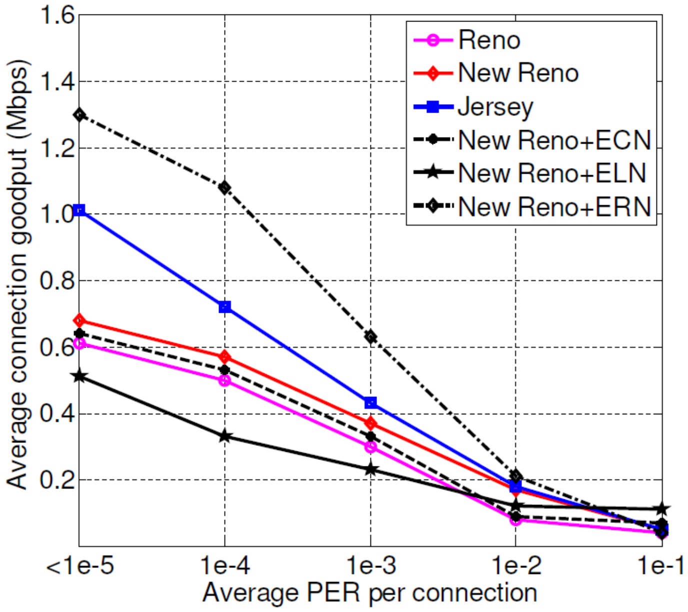


Figure 11 – Average connection goodput vs. average PER in case of six TCP flows and average five hops for each connection.

In the first phase of our work we proposed, as MEMBRANE TCP protocol, an adaptive scheme in which the TCP layer uses New Reno as congestion control algorithm and selects the cross layering techniques ERN or ELN according to the PER that the MAC layer notifies. However, in the MEMEBRANE network, if the number of hops between source and destination remains contained, PER is usually very good thanks to the QoS routing and the MAC scheduling algorithms that optimize the use of the radio channel. As a consequence, in the MEMBRANE network with the newly developed layer 2 and layer 3, most of the time New Reno with ELN would be not useful. Therefore, the complexity of the initial proposal of an adaptive TCP algorithm seems unnecessary in this environment, and the solution of TCP New Reno with the Explicit Rate Notification seems more suitable.

With the integrated simulator, we also verified how the QoS routing and the opportunistic distributed scheduling algorithms work and the performance of the MEMBRANE network in case of concurrent voice calls and FTP traffic. Simulation results showed that the QoS routing is able to reserve resources for the real time traffic, maintaining the required QoS when also data traffic is present in the network: jitter and end-to-end (ETE) delay in case of mixed traffic, voice and FTP, are similar to the results obtained when only voice traffic is present, see for example Figure 12.

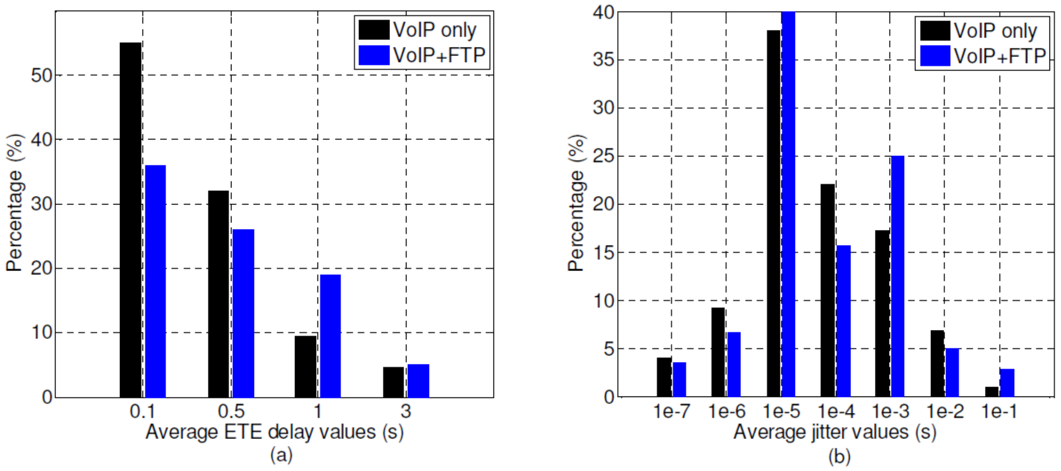


Figure 12 - Simulation results on: (a) distribution of the voice ETE delay values (b) distribution of jitter values, both are shown in case of only voice traffic and with voice and data traffic present in the network.

Simulation results demonstrated that the algorithms devised for the MEMBRANE network properly work when integrated together in a single simulator, allowing performance improvements versus more classical, non cross-layering based approaches.

3.5 MEMBRANE system simulator

3.5.1 MEMBRANE system simulation platform overview

The MEMBRANE simulation platform has been created for evaluation of the throughput and other performance characteristics of the MEMBRANE network as a function of the network topology, antenna techniques on the network nodes, propagation environment, interference, resource allocation strategies and other factors with the help of computer simulations.

Getting representative picture of performance of the MEMBRANE network as a whole requires very extensive computations to take into account all the factors affecting the system performance. To simplify this task, the MEMBRANE simulation platform has been divided into three stages – first for measuring the performance of a single link between two nodes (link-level simulations), then building an abstraction model of the PHY layer performance based on the results of link-level simulations, and finally measuring the system performance with the help of system-level simulations taking into account geographical parameters of the system deployment, mutual interference between the network nodes, where the performance of each link is obtained from the PHY abstraction model with much less computation efforts than using direct link-level modelling of the PHY layer.

In the LLS [MEM D5.1.1] the error performance of a single link between two nodes is measured. The system characteristics that are taken into account in LLS are the channel model, the PHY layer parameters including signal-processing algorithms involved at both ends of the link, numbers of antennas at the transmitter and the receiver. Path loss and shadow fading that in real environment affect the signal strength at the receiver are not modelled in the LLS; instead one explicitly defines the signal power and the noise and interference level at the receiver input. The error performance of the link is measured through modelling of the base-band transmitted signal waveform obtained from encoding of random data, adding noise and interfering signal waveforms to it and simulating the base-band signal processing in the receiver to decode the received data and compare it with the initially transmitted data.

The abstraction model of the MEMBRANE PHY layer [MEM D5.1.2] is an essential part of the System Level Simulator, needed to predict the error performance of the PHY layer using only a small amount of computations. For this purpose a channel quality indicator and a link quality indicator have been introduced to characterize the channel state with as little number of parameters as possible and at the same time allowing prediction of PHY layer error performance with sufficient accuracy. The developed PHY abstraction methodology is based on log-linear approximation of the pre-measured dependence between the channel quality indicator and the link quality indicator. Two channel quality indicators, namely the Mean Instantaneous Capacity within the FEC block and the Mean Mutual Information within the FEC block were considered. FEC coding block error ratio (BLER) was used as a link quality indicator.

In the final stage the system level performance characteristics of the MEMBRANE network are measured is the system level simulations (SLS). The SLS simulator [MEM D5.1.3] includes modelling of multiple network nodes, each node characterized with its geographical position, antenna orientation, antenna system parameters, and a corresponding set of signal processing capabilities. Propagation channels between the nodes are accurately modelled to reflect the basic propagation effects in urban and suburban environments. System performance metrics measured in the SLS include throughput related metrics such as node throughput, network throughput and error performance metrics such as packet error ratio and the probability of the node outage. These basic performance characteristics allow performing various types of comparison between different signal processing and resource allocation techniques applied in the MEMBRANE network. The system level performance evaluation methodology of the wireless communication system with relay stations developed in the course of the MEMBRANE project underlies the Proposal for relay evaluation methodology [C80216m-08_1186] contributed to the IEEE802.16m standard and accepted by the IEEE meeting in September 2008.

3.5.2 Performance measurements results and conclusions

3.5.2.1 Link Level Simulations

The link-level simulator (LLS) [MEM 5.1.1] accurately models the Physical Layer of the MEMBRANE network. The MEMBRANE PHY layer borrowed from the IEEE 802.16e OFDMA allows using all advantages of OFDM modulation and multi-antenna signal processing. One can use frequency and/or spatial diversity either to improve the link robustness to noise and interference, or to perform flexible adaptation of the transmissions to the channel and/or interference environment. The LLS simulator implements multi-antenna signal processing algorithms of various complexity and efficiency in terms of throughput gain and error performance. The LLS simulator implements various receiver types. Interference unaware receiver is simple, but having relatively poor performance. Advanced receivers take advantage of the information about the structure of interfering signals to improve the error performance of the node.

The LLS software also implements a set of different MIMO channel models widely used by the wireless community to evaluate the performance of the communication systems [SCM], [WIN D54], [3GPP]. Implemented channel models capture line-of-sight and non-line-of-sight signal propagation, channel variations due to Doppler Effect.

A set of simulations have been performed to measure the link performance in interference-free environment as well as in presence of the co-channel interference. In the latter case the single interfering node was used to evaluate the system performance. It has been shown that in the strong line-of-sight propagation conditions two antennas at the receiver sight can substantially suppress the strong interfering signal from one interfering node (equivalent SNR performance degradation due to interference is within 2-4 dB), whereas in the non-line-of-sight conditions more antennas are required to provide sufficient suppression of the interference. The examples of performance curves for different antenna techniques and different environments measured in WINNER B5a [WIN D54] channel model are shown in Figure 13.

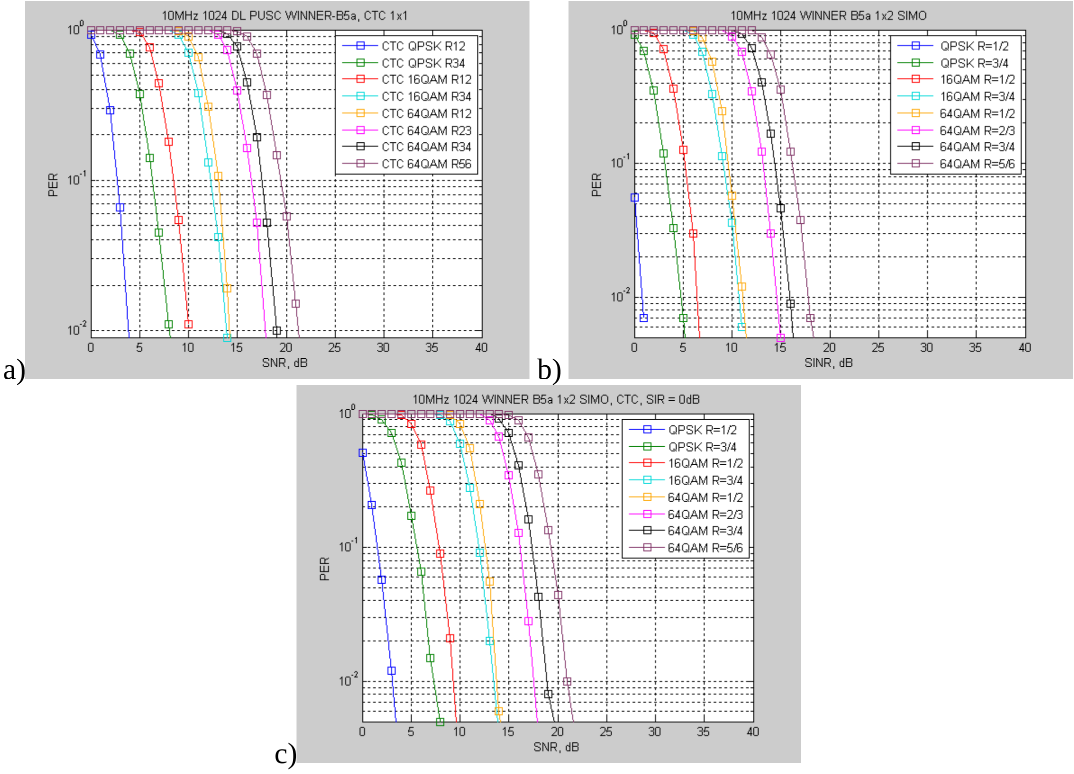


Figure 13 – Performance measurements of the MEMBRANE PHY for the following configurations: a) SISO, no interference b) 1x2 SIMO (MRC receiver), no interference c) 1x2 SIMO, one interfering node (MMSE receiver).

Performance measurements for the mobile nodes have shown that the Doppler Effect produces considerable impact only for high speeds (more than 100 km/h) and degrade the performance of the high-order modulations such as 64QAM with the code rate of 5/6. For lower-order modulations the equivalent SNR degradation due to Doppler Effect is within 1 dB even for 120 km/h node velocity.

Investigations of transmit diversity techniques has shown efficiency of the Alamouti code [Ala98] in the non-line-of-sight channels. In these channels this technique improves the SNR or SINR at the receiving end and therefore can be used to improve the receiving conditions. Another investigated technique – the Spatial Multiplexing (SM) [802.16-2004] did not show substantial SNR or SINR improvement over the SIMO system with the same number of receiving antennas. However, this technique has advantage of the higher maximum data rate in the channels with rich multi-path propagation, and therefore may be used to increase the data rate on links with good SNR or SINR.

The results of the analysis performed with the help of link level simulator have been used as a basis for the physical-layer abstraction model and system level simulations as well as for prototyping work as test vectors and guides for algorithm implementation.

3.5.2.2 PHY layer abstraction

The PHY abstraction model [MEM D5.1.2] is essential component of the system-level performance evaluation of the OFDMA-based MEMBRANE communication system [802.16]. The PHY layer abstraction methodology has been developed to incorporate the results of the link level performance evaluation into the system level part of the simulation platform. The proposed methodology allows dramatically reducing the amount of computations needed to estimate the error probabilities of signal transmissions sent trough a channel with given characteristics and multi-antenna techniques. The high-level diagram of the PHY abstraction model operation is shown in Figure 14.

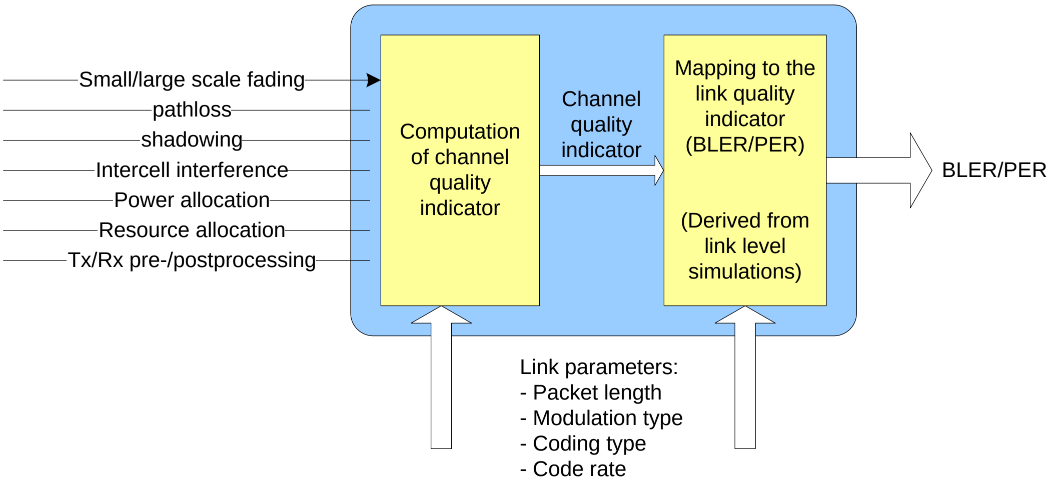


Figure 14– Operation diagram of the PHY abstraction model

The developed PHY abstraction methodology is based on log-linear approximation of the pre-measured dependence between the channel quality indicator and the link quality indicator. Two channel quality indicators, namely the Mean Instantaneous Capacity (MIC) within the FEC block and the Mean Mutual Information (MMI) within the FEC block has been considered, and FEC coding block error rate (BLER) was used as a link quality indicator. Examples of the scattering diagrams and the log-linear approximation curves for selected modulation and coding schemes are shown in Figure 15.

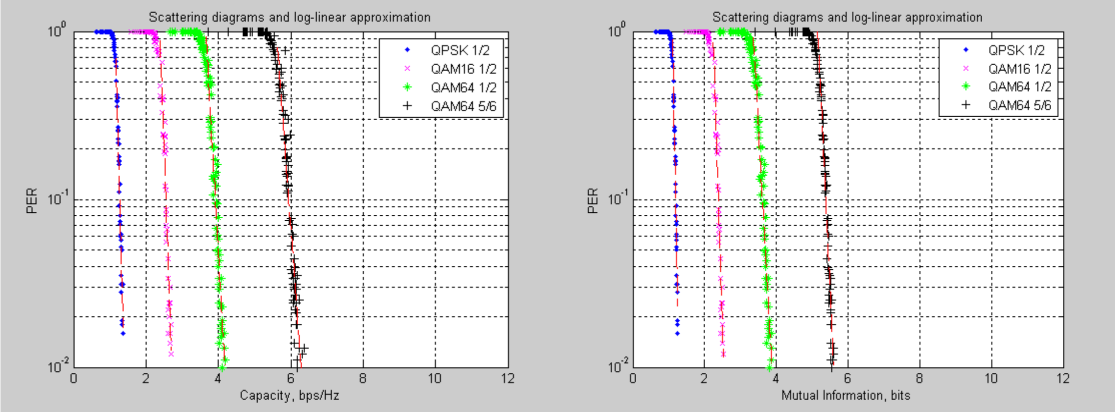


Figure 15– Measurements of the PHY abstraction model parameters for selected modulation and coding schemes

The exact ready-to-use log-linear approximation parameters for the developed PHY abstraction models have been derived for all modulation and coding schemes. It has been shown that these parameters do not depend significantly on the channel models and on the multi-antenna techniques employed. Therefore the performance of the whole range of signal-processing techniques typically used in modern wireless communications can be estimated with the help of the developed PHY abstraction model with the single set of parameters.

The performance predicting ability of the MEMBRANE PHY abstraction model has been tested. Examples of measured and predicted dependencies of average PER vs. SNR are shown in Figure 16. Both MIC and MMI channel quality indicators appear good enough for predicting the FEC block error probability. The equivalent SNR inaccuracy of the prediction is within 1 dB for most of the channel models and multi-antenna techniques and achieving 2 dB for the least robust modulation orders and the SM antenna technique. Therefore Mean Instantaneous Capacity based indicator has been adopted for use in the SLS simulator as simpler and less computationally expensive.

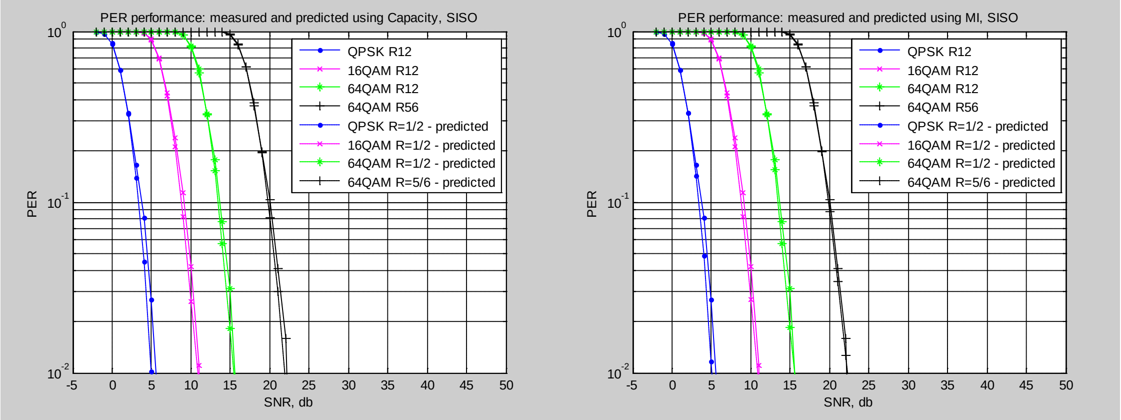


Figure 16– PHY abstraction prediction accuracy measurements

3.5.2.3 System Level Simulations

The most important results have been obtained in the process of the system level performance evaluation [MEM D5.1.3] of the MEMBRANE network schematically shown in Figure 17.

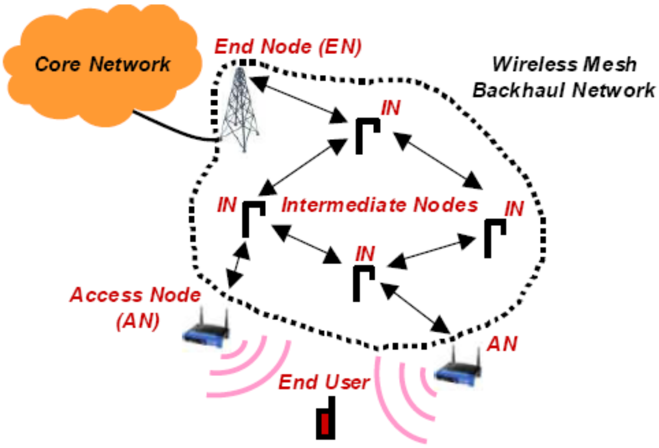


Figure 17– MEMBRANE network

Below we summarize the results obtained in the system level simulations of the MEMBRANE network performed for different network and propagation scenarios.

First set of the system level simulations (SLS) has been performed for the Two-hop network scenario, where the performance impact of intelligent relaying mode selection, cooperative relaying and the data-splitting algorithm has been investigated. The considered structure of the MEMBRANE network in the two-hop scenario is shown in Figure 18. In this scenario the MEMBRANE network covers relatively small area, and transmissions between the End Node and any of the Access Nodes may be done with one or two hops.

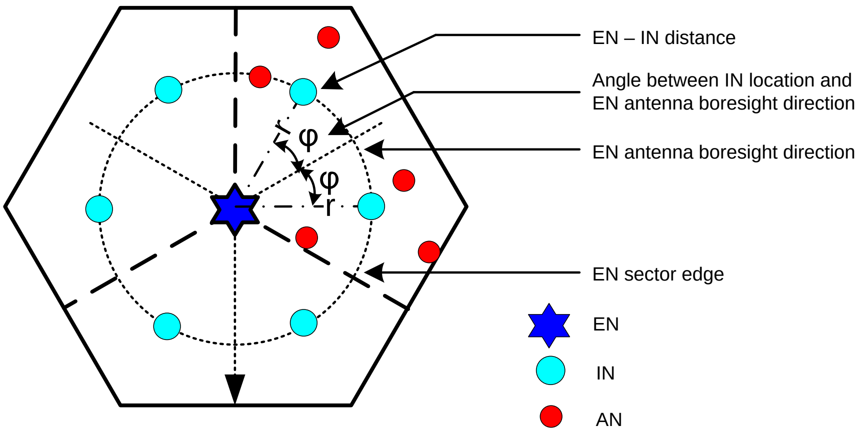


Figure 18– Structure of the hexagonal cell of the MEMBRANE network in the two-hop scenario.

In the two-hop network scenario the task of optimising of the routing and scheduling can be solved via extensive search over all possibilities. For this purpose in the SLS a set of relaying modes [Mal08a] has been defined to reflect all such possibilities, and it has been clearly shown that careful intelligent selection of the relaying modes for each Access Node allows improving the aggregate network throughput considerably (up to 2.5 times). The main factor of the performance improvement is the spatial reuse of the spectrum resources between the different network nodes. Besides, intelligent selection of the relaying modes completely eliminates the access node outage.

On the other hand employing the cooperative relaying techniques for the considered two-hop scenario did not produce any impact on the system throughput because the cooperative relaying modes are preferable only for small number of the Access Nodes. For the majority of the Access Nodes other relaying modes (division or simultaneous) appeared more effective.

The MEMBRANE network may also benefit from the two-hop transmissions using spatial multiplexing of the data stream onto several relay nodes simultaneously and following collection of the relayed streams at the destination node, again using the spatial multiplexing technique. This is shown by the performance measurements of the Data Splitting Algorithm [MEM D4.1.2]. Investigation of system level performance of the data splitting algorithm for two-hop scenario shows that the DSA provides the system throughput improvement in comparison with the direct link and the hard switching between the direct transmission from the end node to the access nodes and the transmission using the best relay technique. DSA is shown to outperform Hard Switching algorithm and Direct Link transmission algorithms by 15% and 30% respectively in terms of average cell throughput and by a factor of 2 and 7 respectively in terms of outage (measured at the least possible data rate 0.167 bps/Hz).

Another set of simulations has been performed in Multi-hop network scenario. Hexagonal model of the MEMBRANE network in the multi-hop scenario is shown in Figure 19. The performance of different antenna types, beamforming algorithms, as well as routing and scheduling algorithms has been measured in this scenario. Below we summarize the obtained results.

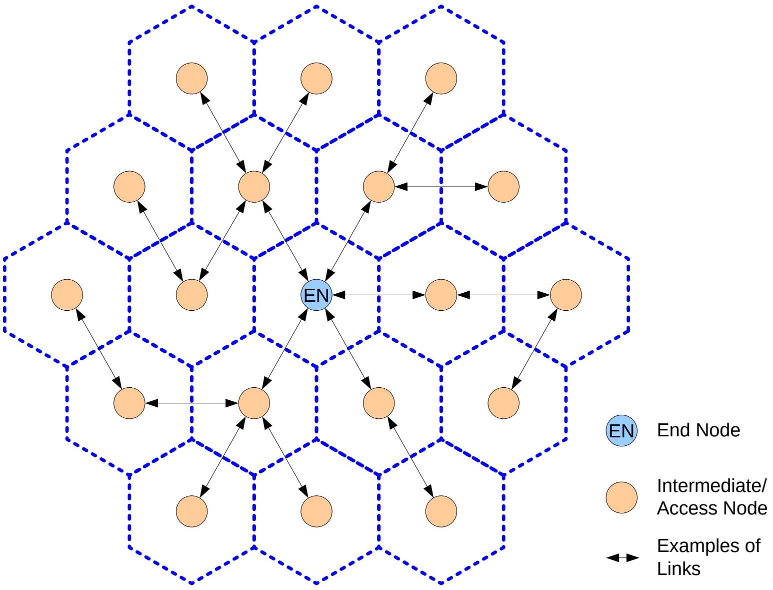


Figure 19– Hexagonal model of the MEMBRANE network in the multi-hop scenario

Multi-hop network scenario has been used for evaluating the performance improvement due to use of directional antennas at the network nodes. Considerable network throughput increase due to use of steerable directional antennas at the network nodes has been observed. Depending on the above rooftop (ART) or below rooftop (BRT) propagation scenario, the antenna beamwidth, the distance between the network nodes and the accuracy of adjustment of the beam direction, the throughput benefit may be 1.5 to 4 times in comparison with the omnidirectional antennas. Another conclusion here is that sectored beam-steering antennas with six sectors provide approximately the same performance improvement to the systems as the continuous beam-steering antennas with the same beamwidth (35 degrees at half-power level).

The performance impact of exploiting antenna arrays on the network nodes has been investigated also. Considerable performance improvement over the network with omnidirectional nodes has been achieved with adaptive antenna arrays (capable varying both the phase and the magnitude of the signals from each antenna elements). For ART scenario the system level throughput performance improvement of 12-element adaptive antenna arrays over omnidirectional antennas may achieve 3.5 times for inter-node distances about 2 km, and the coverage improvement at the same throughput performance level may exceed 6-7 times. For BRT scenario the throughput improvement may achieve 6-10 times for distances 1-1.5 km, and the coverage improvement achieves 4 times.

Comparing the performance of the directional antennas and the adaptive antenna arrays, simulations show that in ART propagation scenario directional steerable antennas with 35 degrees beamwidth provide almost the same throughput performance as the 12-element adaptive antennas arrays. On the other hand, in BRT propagation scenario 6-element adaptive antenna arrays with rough beamforming slightly outperform the 6-sector steerable antennas with 35 degrees beamwidth. However, the use of 12-element adaptive antenna arrays with fine per-subcarrier beamforming almost doubles the throughput in comparison with 6-sector steerable antennas.

Considering different beamforming algorithms for adaptive antenna arrays in application to OFDM physical layer, we compared the performance of rough beamforming performed in the entire frequency bandwidth and fine per-subcarrier beamforming. In the ART propagation scenario there were no significant performance difference observed between the two algorithms, and therefore rough beamforming may be recommended as simpler one. In the BRT propagation scenario fine beamforming results in 1.5 times throughput improvement over rough algorithm and therefore we recommend using fine beamforming for the below rooftop scenario having rich scattering environment.

Performance measurements for phased antenna arrays capable of varying only the phases of the signals on its elements show their poor performance in the BRT propagation scenario with rich scattering environment. In the ART scenario 6-element adaptive antenna arrays considerably outperform the 12-element phased antenna arrays.

Performance measurements of scheduling algorithms show almost equal performance of the “As Soon As Possible” (ASAP) [Tao05] and Clique [Sal05] scheduling. Both of these algorithms take advantage of spatial reuse of transmissions made on different network links, however, the Clique scheduling has prohibitive computational complexity for large networks and therefore we recommend simpler ASAP scheduling for use in wireless backhaul networks. On the other hand employing directional antennas also leads to more intensive usage of spatial reuse between different network links in comparison with the omnidirectional antennas, especially for ART propagation scenario. Therefore use of the maximum per-path throughput routing and the ASAP scheduling or the like algorithms is recommended for such networks.

3.6 MEMBRANE Demonstrator

3.6.1 General Overview of the MEMBRANE Demonstrator

The MEMBRANE Demonstrator involves the development of certain algorithms over hardware platforms in order to provide a concrete proof of these concepts and demonstrate the feasibility of future implementation of these technologies to next generation wireless telecommunication backhaul networks. Two features/algorithms have been selected for demonstration into two distinct prototype platforms, namely the PHY and the MAC demonstrators.

The performance gains provided by multiple antenna and multi-hopping techniques are demonstrated with the PHY prototype by implementing the Data Splitting Algorithm (DSA) developed in WP4.1. The enhancements offered with opportunistic scheduling and routing protocols are shown with the help of the MAC demonstrator by implementing the Distributed Scheduler proposed in WP4.2.

The PHY demonstrator realizes the Data Splitting Algorithm (DSA). The DSA describes a transmission technique from the base station (end node) to the subscriber station (access node) in the system exploiting multiple relaying stations. The data transmission can be done directly between the base station and the access node or in two hops by first transmitting from the base station to one of the relay stations and then transmitting from the relay station to the subscriber station. Every node in the network is equipped with multiple antennas and can support transmission and reception of multiple parallel spatial streams by using linear closed loop MIMO processing. Different spatial streams may be routed differently (e.g. some streams directly and some streams through relays) from the base station to the subscriber. The DSA solves an optimization problem by optimally defining transmission routes for the given number of the spatial streams. The corresponding transmit and receive antenna weight vectors are calculated with taking into MIMO channel realizations between nodes all under the constraint of zero interference between different spatial streams. More details about the DSA along with rigorous mathematical derivations may be found in [MEM D4.1.2].

For the PHY demonstrator implementation a configuration of the system with a base station, two relay stations and a subscriber stations has been considered. Each node in the network was supposed to have two antennas for both transmission and reception and thus to support two spatial streams. Therefore this setup results in six different combinations of routes for two spatial data streams which are shown in Figure 20. For the given MIMO channel realizations between all stations the DSA analyzes efficiencies of all combinations and selects the combination of two spatial streams which maximizes the system throughput.

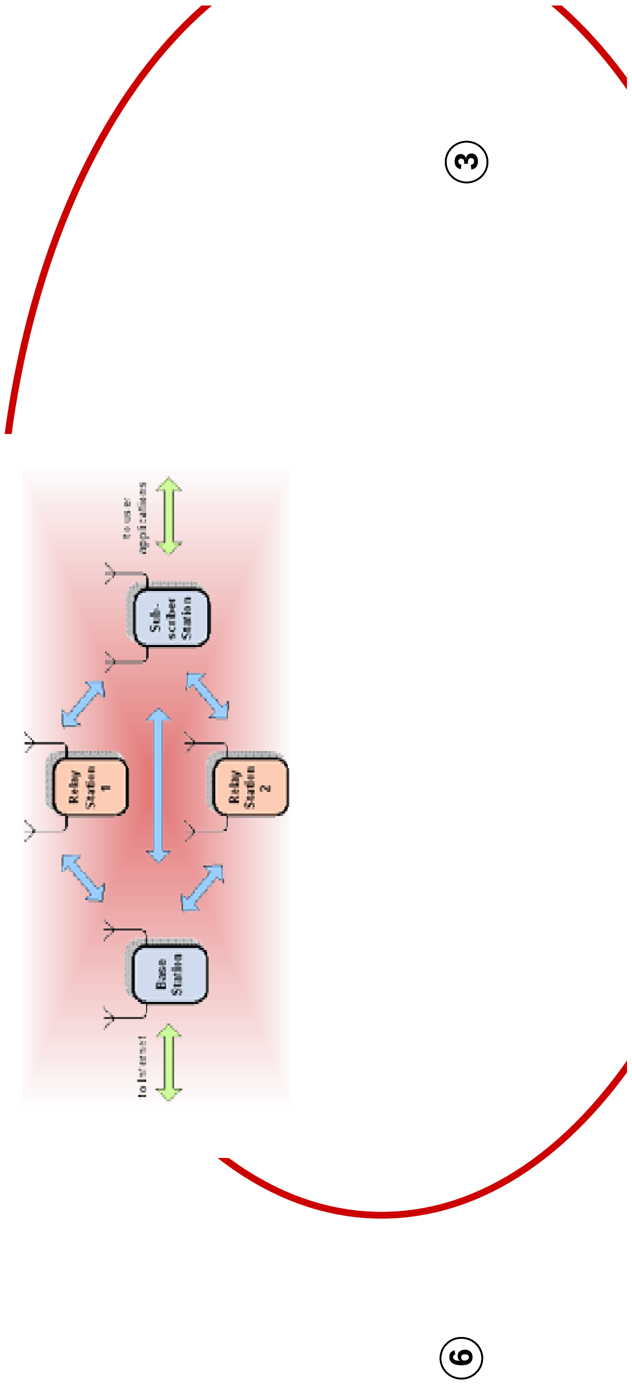


Figure 20– DSA prototype transmission modes

To provide a proof-of-concept implementation of the DSA algorithm for the selected configuration of the network a real time hardware-software emulator has been developed. The block diagram of the developed emulator and a picture of its operation are shown in Figure 21.

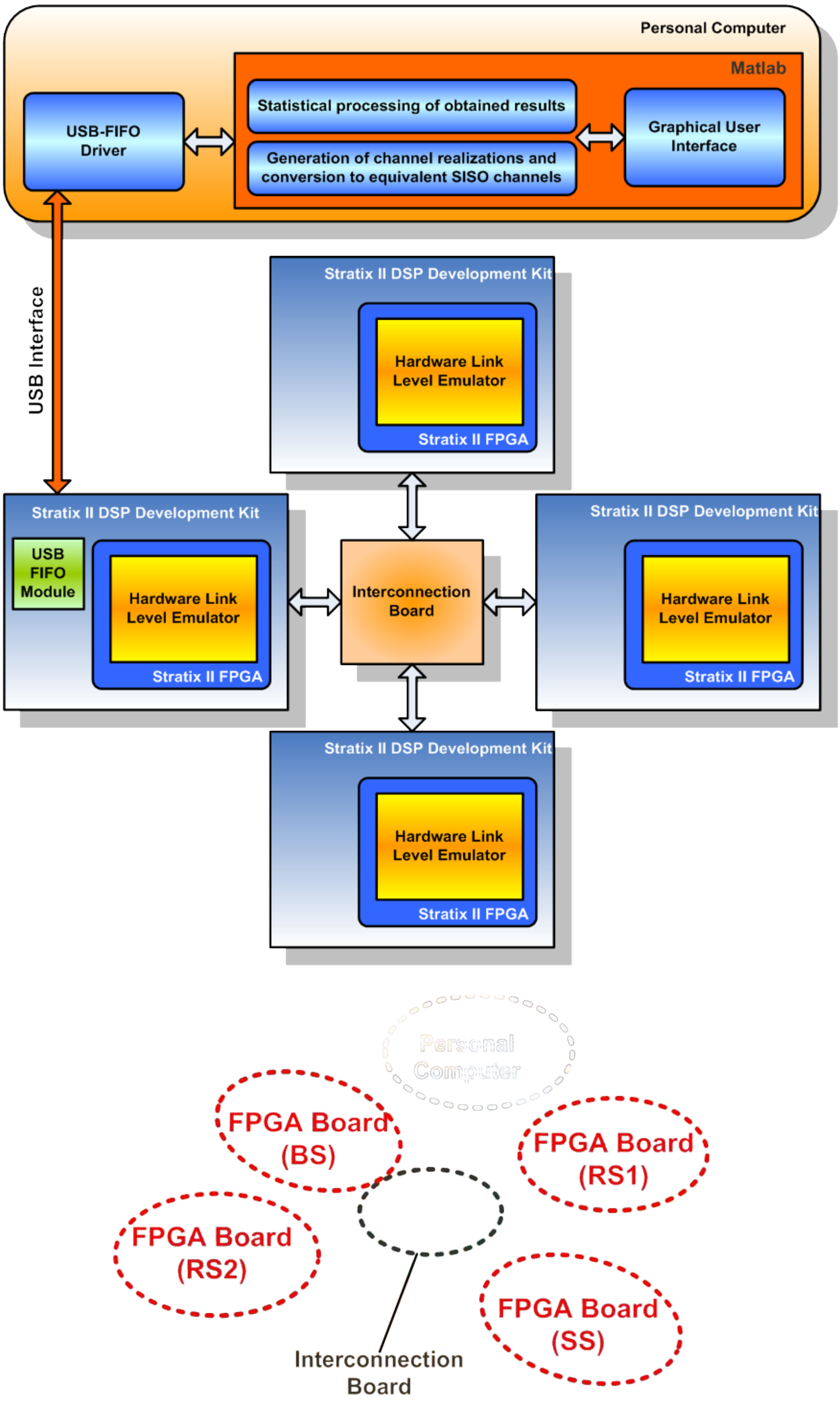


Figure 21– Block diagram of the developed emulator and a picture of its operation

As it is illustrated in Figure 21 the PHY demonstrator consists of four Field Programmable Gate Array (FPGA) boards hooked up together by dedicated interconnection board and one of the FPGA boards having also a USB interface link to the personal computer (PC). The architecture of the emulator has been selected with the goal to execute non time critical tasks as PC software functions and to implement the computationally intensive routines as hardware modules on the FPGA devices. The partitioning between the hardware and the software parts has been made with taking into account the properties of the DSA algorithm. As it was outlined in the DSA description it provides a set of transmit and receive antenna weight vectors to perform simultaneous transmissions of several parallel data streams between different nodes. A new set of the antenna weight vectors has to be obtained for each new set of channel realizations between nodes. After the weight vectors are calculated the original MIMO channel may be represented by equivalent SISO channels without loss of generality. Thus the antenna weight vectors calculation has to be done once per each new channel realization and this operation was realized in Matlab computational environment as a software procedure on the PC. After that the calculation of the effective SISO channels characteristics is also done in Matlab software and then the FPGA boards are used to emulate effective SISO links and estimate their error performance (typically bit error rate). To be able to emulate performance of the individual links in the real time the hardware link level emulator (HLLE) has been developed. The HLLE constitutes a SISO OFDM/OFDMA simulation pipeline implemented in hardware and includes a transmit part, a channel emulation logic, and a receive part. The simulation time of the HLLE can be as high as 100 Mbps for the considered FPGA implementation and thus meets the real time requirements. More details about the HLLE can be found in [MEM D5.2.2]. After the HLLE completes the simulation of the individual effective SISO links, the results are sent back to the PC. The PC performs statistical processing of data and then presents the results in the graphical user interface (GUI).

From the complexity implementation point of view, the central block of the PHY demonstrator is the HLLE. That block required maximum implementation efforts. The HLLE is a synthesizable System-on-Chip (SoC) component that can be integrated into FPGA systems. The HLLE requires from 15K to 17K of FPGA equivalent logic elements depending on the FPGA implementation technology. The implementation of the embedded software for the NIOS processor, the design of the USB-FIFO module and the interconnection board, and the development of the software for the control PC were standard engineering tasks that required significant effort but not any serious insoluble obstacles.

A framework for scheduling has been established within MEMBRANE, from which the novel MEMBRANE Distributed Scheduling (MDS) algorithm has been deduced. The algorithm is basically composed of four phases: utility exchange, initial decision, initial decision exchange and final decision. For simplification, the one-round version of the algorithm has been selected for implementation. For the demonstrator, two different metrics are used as utility functions: Signal-to-Interference Ratio (SIR) and Proportional Fair (PF). This leads to two implementation versions of the MDS algorithm.

The MAC demonstrator of MEMBRANE targets to validate the behaviour of advanced protocols of the projects that aim to optimize the resource allocation schemes of the wireless multihop backhaul network. The MEMBRANE Distributed Scheduler (MDS) has been developed, implemented and evaluated in two phases.

During the first phase, the wireless transmission medium emulation has been provided by a standard 5-port switch. All stations, represented by a standard laptop running Linux Operating System, are attached to the switch in charge to offer simplistic and equal receiving and transmit capabilities to all stations at the physical layer level. In the second phase of the MAC

Demonstrator development, the central wireless medium entity is replaced by a hardware platform to support transmissions compatible to the IEEE 802.16e standard. The platform contains 4 custom hardware boards with embedded parallel DSPs and network processors that can support the PHY and MAC functionalities required to support the MDS algorithm. The platform is completed with 2 additional boards: a commercial FPGA board and a custom made passive hardware board for interconnection.

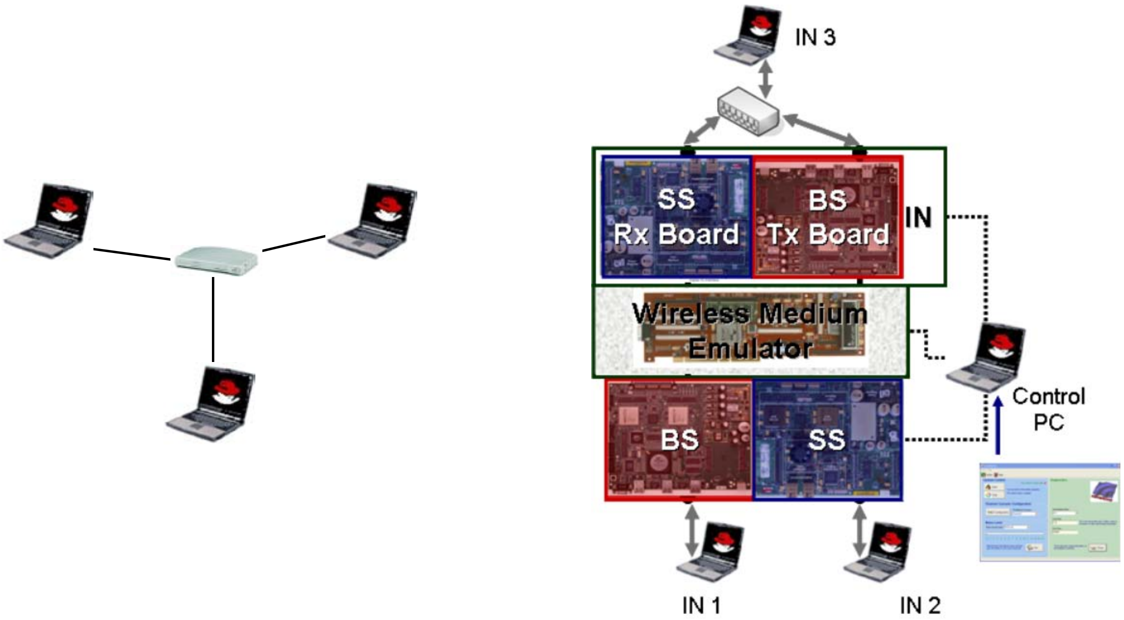
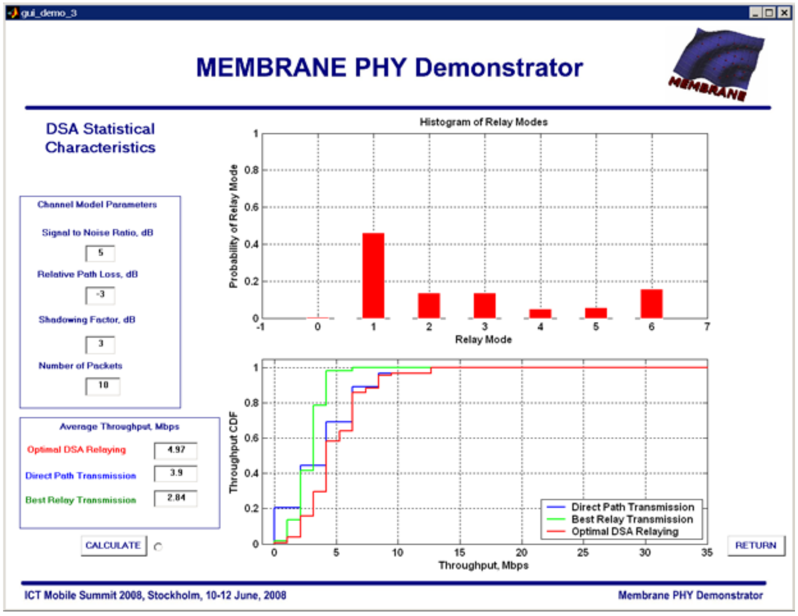


Figure 22– MEMBRANE MAC Demonstration Hardware Configuration (Phase 1 and 2)

3.6.2 Performance Results

The PHY demonstrator was used for the comprehensive evaluation of the DSA performance for the considered configuration of the MEMBRANE network. Taking into account that there are four nodes and each can support two transmit and two receive antennas it may be seen that there are potentially very many parameters in the system which may be varied. So there are totally very many combinations of parameters values and not all the combinations can be tested. The goal was set to define a minimum subset of the essential parameters which changes lead to different behaviour of the DSA algorithm. Three such parameters have been defined: signal-to-noise ratio (SNR) of the BS to RS1,2 and RS1,2 to SS links (common for all these links), average path loss difference in the direct link (BS to SS) relatively to the other links, and a path loss shadowing fading factor common for all links. These three parameters could be changed through the graphical user interface (GUI) together with the number of the packets to be sent over the network. All other parameters of the simulation have been fixed. The channel model between stations was above rooftop to above rooftop Winner B spatial channel model. The emulated PHY layer was OFDMA PHY layer with 512 subcarriers and 5 MHz bandwidth. The GUI was used not only to change the values of the essential parameters but also to display the calculated statistical characteristics of the MEMBRANE network performance. The example of the MEMBRANE PHY demonstrator GUI screenshot is shown in Figure 23. The statistical characteristics include histogram of the transmission modes distribution and the CDF of the network throughput with the DSA algorithm. For comparison the CDF of the throughputs for direct path only transmission protocol (transmission mode 1 in Figure 20) and best relay transmission protocol (protocol which chooses the best transmission mode from modes 2 or 3 in Figure 20) are displayed at the GUI window.

Also the average throughputs for three investigated transmission protocols are calculated and presented at the GUI. The direct transmission and the best relay transmission protocols can be considered as traditional single user MIMO schemes which are a subset of the transmission modes provided by the DSA. It can be seen from the Figure 23 that the DSA includes three additional transmission modes (4, 5, 6) sending two data streams through different spatial routes.



Channel Model Parameters

Signal to Noise Ratio, dB: 5

Relative Path Loss, dB: -3

Shadowing Factor, dB: 3

Number of Packets: 10

Average Throughput, Mbps

Optimal DSA Relaying	4.97
Direct Path Transmission	3.9
Best Relay Transmission	2.84

Figure 23– MEMBRANE PHY Demonstrator Graphical User Interface

Several evaluation scenarios with different parameters sets have been selected and the performance evaluation results for these scenarios have been obtained with the help of the PHY demonstrator. The conclusion can be drawn that due to its flexibility the DSA provides significant performance improvement over the direct transmission and the best relay methods for all the situations except when the strong direct path between BS and SS is dominating. When the strong direct path is present the performance of the DSA will be identical to the performance of the direct transmission protocol. With the blocked direct path the DSA outperforms best relaying techniques especially for the high SNR regime where the mode sending two data streams through different relays is preferably used. For the low SNR and a blocked direct path the performance of the DSA is close to the best relay technique because the corresponding transmission modes provide the largest throughput. When the propagation loss of the direct path is just several dBs below the path losses of other links then the preferable modes are the modes sending data simultaneously through one of the relays and direct path (transmission modes 4 and 5 in Figure 20). For the low SNR regime and the slight direct path degradation all the modes are selected approximately with equal probabilities with the direct transmission starting to dominate with the direct path improvement. The shadowing factor impact is that when the shadowing factor increases it leads to more uniform distribution of different modes because of the larger fluctuations of the characteristics of individual links. In the last case the throughput improvement provided by the DSA relatively to the other schemes increases due to mode diversity gain.

Performance results of the MAC Demonstrator have been obtained using phase I and phase II hardware configurations for the MDS algorithm. Beside the test case of Round Robin (RR) scheduling, the two versions – SIR and PF – of the algorithms have been implemented.

In the single flow experiments, the RR approach performed its best with UDP while TCP due to its connection oriented approach and congestion control algorithms exhibited a higher achieved throughput. Concentrating on TCP application, it is evident that, independently to the approach followed, the larger the data packet, the higher the anticipated achieved throughput.

The results obtained for the 2 crossed data flow scenario show that while in the RR approach the bandwidth is fairly allocated among the two flows both from delay and delay deviation perspective when SIR or PF approach is applied a clear favouritism is presented. In the scenario where two different data flows compete for the same resource, using UDP, an emphatic favouritism is depicted to a specific traffic directions independently of the MDS protocol used. Also, the aggregated throughput is doubled for SIR and almost tripled for the PF case compared to RR scheduling. In TCP, the previous favouritism is equally emphatic due to the controlling effect of the TCP protocol.

It becomes clear that the MDS algorithm can manage the influence of the propagation conditions and provide fairness to the nodes trying to access the network. However, the influence of the control transport layer mechanism is evident which leads to requiring alternative modules in charge of joint scheduling and routing. In any case, the MDS algorithm is a robust mechanism and its preferred mode of operation is with large data packets.

For the MAC Demonstrator, the complexity of the novel virtual driver layer designed to incorporate all required MDS functionality is relatively minimal. The implementation approach selected through the development of this driver offered significant flexibility to the development, evaluation, implementation and integration of the algorithm. The driver component can be a stand alone module, mounded at run time and can directly manipulate the Ethernet driver. It can capture and process packets from the PHY or create specific custom packets and schedule them for transmission. With the advantages offered from the openness of the Linux OS, it has been possible to extend a popular network device driver with the features of the MDS algorithm. The integration of the protocol has been simple. It can be easy transported to another platform or modified to include more advanced features. This implementation simplicity shows that the MDS algorithm constitute a good candidate for integration to future backhaul networks.

3.7 Dissemination, exploitation and impact

The studies within MEMBRANE on wireless backhaul networks addressed the following research questions/objectives:

- The understanding of the fundamental capacity limits of these networks
- The study of optimal network topologies, especially in demanding propagation environments and under low power or low cost constraints
- The development of efficient, reconfigurable routing and scheduling algorithms that maximize QoS, power utilization and service fairness
- The development of reconfigurable MIMO and multihop techniques for throughput maximization

- The efficient resource utilization by combining intelligent antenna, routing and scheduling techniques
- Proofs-of-concept of the developed network design and algorithms via a comprehensive system-level evaluation platform and hardware demonstration

The analysis, developed concepts, algorithms, systems design and implementation findings have been extensively disseminated in journal and conference publications (see Annex A), have generated a number of invention (patent) submissions and standards contributions (see Annex B) and were demonstrated using the MEMBRANE proof-of-concept prototype (see Figure 20-Figure 23).

The results obtained in the course of MEMBRANE are being integrated into existing and newly established courses (including lab courses) on wireless networks by the academic partners, and they will form the basis for student theses at the MSc and PhD levels.

In MEMBRANE, the development of a number of algorithms, system architectures and simulation environments by different partners has been a significant task required to appropriately assess the proposed concepts and techniques.

Alcatel-Lucent has developed novel cross layer MIMO and multihop concepts and a Matlab simulation environment–both the link and system level elements– in order to assess the proposed techniques. The algorithms and simulator will be exploited is future studies for further investigation and evaluation of next generation multihop and MIMO wireless network performance both in the context of evolving wireless standards and for future generation systems.

Intracom benefited from the partial development of transceiver chains in different simulation environments: a command line interpreter (MATLAB) and an event-driven software (NS-2). However, Intracom plans to further investigate the exploitation of link level results to a system level model through PHY layer abstraction. A methodology framework has been established within MEMBRANE showing how the link and system level simulation can be combined to achieve more reliable performance results. This approach in simulation modelling is also defined in several evaluation methodology documents of various standardization bodies. Using the MEMBRANE framework as a guide, relevant simulation models can be drawn that can relate the outcomes of the current internal research to appropriate evaluation reports candidate for standardization contributions. Of course, the simulation methodology and framework developed within MEMBRANE need to be refined for the evaluation of current systems under development or under research. The issues raised from the simulation work in MEMBRANE are useful for the evaluation and validation of several in-house link and system level platforms.

The MEMBRANE software system level simulation platform has been developed by Intel in collaboration with other MEMBRANE partners, who provided valuable inputs concerning definitions of the simulation scenarios, development of the signal processing and relaying techniques as well as the theoretical analysis thereof. Considerable achievements were the development of the simulation methodology, which has been disseminated externally through the contributions to evaluation methodologies for the standardisation bodies like IEEE. Based on this methodology the Intel team participating in the MEMBRANE project has contributed the Proposal for relay evaluation methodology [C80216m-08_1186] to the IEEE802.16m standard. This contribution concerning the performance evaluation methodology for the WiMAX system with relay stations in each cell has been adopted by the IEEE meeting in September 2008.

The division of the simulation platform into three stages, namely the Link-level part, the PHY abstraction model, and the System-level part produced a universal simulation platform that can be used for performance evaluation of many types of wireless data communication systems.

Simulation of different types of communication systems requires adjustments of the platform concerning only the modelling of the appropriate physical layer and the propagation channels for appropriate frequency bands. At the same time the system level simulator does not depend significantly on the physical layer specifics of a particular communication system and may be used as a stand-alone tool. This considerably simplifies investigations of the next generations of the wireless communication systems.

Several valuable simulation results and conclusion have been obtained with the help of the developed MEMBRANE system simulation platform. The efficiency of multi-hopping to improve the overall network spectral efficiency has been demonstrated. Results of performance evaluation of various antenna techniques at the network nodes demonstrate the potential of exploiting directional and adaptive antennas for further improvement of the capacity of wireless communication systems. These results proving the efficiency of the MEMBRANE approach have been disseminated through a number of conference publications and participation in the exhibitions. Based on the results obtained with the help of the MEMBRANE system simulation platform several contributions regarding the efficiency of the various relaying techniques have been submitted to the IEEE 802.16m standard.

In addition to the MEMBRANE system level simulator, Cefriel and Imperial College have developed a complex simulation environment, named “integrated simulator” that integrates in a single simulator all the innovative MEMBRANE algorithms: L2, L3 and L4 MEMBRANE protocols with a simplified version of MEMBRANE L1. With the integrated simulator it is possible to simulate a MEMBRANE network with any topology of nodes, in which different bundles of real applications can run, allowing performance evaluation and monitoring of a broad range of parameters. The integrated simulator will be exploited in future studies for further investigation and evaluation of next generation multihop wireless network performance, in particular when the cross-layer approach is of primary importance.

The development of the MEMBRANE prototype has been carried out by Intracom and Intel in collaboration with other industrial partners of the consortium, i.e. Alcatel-Lucent and valuable inputs have also been provided from Imperial College and Cefriel.

The MEMBRANE PHY demonstrator is a flexible hardware-software platform for real time evaluation of the wireless communication systems. The whole platform and in particularly the hardware link level emulator (HLLE) is planned to be reused within the other research and development projects. The presentation of the MEMBRANE PHY demonstrator and the HLLE design approach at the ICT Mobile Summit 2008 [Mal08b] has attracted a substantial interest and the perspective of future potential research projects has been discussed with representatives of several European R&D organizations.

The prototyping activities completed in MEMBRANE are disseminated both internally and externally through the exploitation of its outcomes in product development or, as a basis for running or future research projects. The demonstration platform currently established facilitates the study of similar resource allocation problems. With the development of an advanced meshed platform representing several nodes of the network and capable to support different communication and interconnection modes, the MEMBRANE platform provides a stable testing environment for future prototyping activities. Also, another valuable asset for further exploitation is the independence of the high-layer technique towards the underneath hardware. The evaluation of the complex resource allocation techniques spanning from scheduling to routing with integrated power control can be carried out independently of the undergoing hardware. Hence, it becomes easy to upgrade the MEMBRANE techniques with other novel resource allocation techniques for evaluation. To this end, the hardware independence of the cross-layer process and the implementation methodology used for the distribution of relevant information among layers can be further enhanced. Finally, the simulation results and blocks developed in NS-2 have been crucial in the integration of the prototype. This approach is a reliable implementation method that can be iterated for similar resource allocation algorithms.

Using as background the research framework of MEMBRANE, future common dissemination activities can be established, including further collaboration in similar projects, tackling research and development of wireless telecommunication systems beyond 3G. Within the project, the exhibition of the MEMBRANE demonstration platform has been a joint task of Intracom, Intel and Alcatel-Lucent showing that such common actions can be carry out to promote results and work shared among these companies.

4 MEMBRANE network design recommendations and future research directions

4.1 Fundamental performance limits of multi-hop (MIMO) relay networks

Our analytical analysis provides system design guidelines for MEMBRANE in particular and future cooperative communication schemes in general.

In particular, asymptotic (in number of relays) network capacity results can be used to estimate the throughput one can hope to pass through a large relay network. This kind of analytical tool is extremely useful in network resource allocation planning and deployment scenarios.

Further, we have demonstrated that a trade-off exists between the channel state information required at relay level and the number of relays that must exist in the network in order to mitigate the effects of interference and fading. This trade-off can be used to assess the number of relays to be deployed or the amount of channel training required in the system.

Our asymptotic (in signal-to-noise ratio) analysis provides a code design criterion to achieve optimal performance (in terms of the diversity-multiplexing trade-off (DMT)) that can be implemented to give optimal performance. Our code design criterion can be met by using a combination of linear transformations at relay level and a coding scheme that is DMT optimal for a point-to-point channel with appropriate rate.

Further, our code design criterion is robust against channel modelling errors in the sense that it is guaranteed to be optimal for a very large class of wireless channels. Hence, codes designed to meet our criterion perform well in a wide range of propagation environments, which is very valuable from an implementation point of view.

Our work in the framework of WP3 can be cast into the context of dominant error events, a concept originally introduced by Gallager in the context of multiple access channels (MACs) [Gal85], and recently applied to the frequency selective MACs in [Cor07,Gal85,Gar06]. We believe that the application of dominant error events to general wireless networks could provide an efficient way to tackle problems that are not analytically tractable with other methods. Multi-antenna extensions of the problems that WP3 looked at should be analyzed using these tools to see if analytical solutions can be obtained.

The tools we developed to tackle general fading distributions can be applied to many other problems including asymptotic analysis of frequency selective channels, multiple access channels and interference channels.

A further analysis of speed of convergence to asymptotic limits could be very useful for practical systems.

4.2 Multi-antenna link signalling and routing

In the framework of the multi-antenna signalling and routing studies, we proposed a number of approaches for applying multi-antenna techniques to a high data rate wireless backhaul transmission. Our investigation addressed different issues: the impact of cross-layer optimization where routing and physical layer algorithms are jointly designed, the impact of the estimation error on different space-time approaches, the impact of the interference and the value of properly designed cancellation techniques at the receiver side, the impact of the propagation scenario and the impact of relay-aided transmissions.

The main result of this investigation was that, even under the assumption of a very focused application as a backhaul network transmission is, the choice of the technique to deploy is highly scenario-dependent. For example, precoding-based techniques, such as Data Splitting Algorithm, are very effective under the assumption of accurate channel estimation, whereas approaches based on interference cancellation are more suitable with fast fading channels or when a dedicated feedback channel is not available.

Differently from previous proposed schemes where independent streams are directly sent to the destination or sent to the relay and then forwarded to the destination, in the DSA case the independent streams are “routed” to different relays and at the same time sent directly to the destination in order to maximize the throughput. This approach is particularly appealing for correlated channels, where, due to the low rank of the channel matrix, it is not possible to achieve the maximum number of independent transmitted streams given by the minimum between transmit and receive antennas.

Also the deployment and propagation scenarios play a very important role. For instance, the joint routing and physical layer through DSA is beneficial only when there is a minimum number of intermediate nodes, otherwise the less computational complex not cross-layer technique based on 2-path relaying can be preferable.

4.3 Routing, scheduling and power control for wireless backhaul network optimisation

Most of the algorithms derived in WP4.2 are highly generic and can be easily applied in any kind of wireless backhaul mesh networks, such as MEMBRANE. Their performance has been evaluated analytically and/or by extensive simulations. Moreover, several concepts and algorithms derived in WP4.2 have been implemented on the MEMBRANE platform to verify their applicability in a more realistic MEMBRANE network. Nevertheless, most of the ideas, concepts and findings derived in this WP are very novel and therefore further research may required for their better understanding and further improvement.

Regarding the theoretical framework on PFS, the analytic results hold for general flat-fading environments. These formulas have the great practical and theoretical interest of being mathematically simple and tractable. Our theoretical results and findings provide guidelines and analytical support on system design, simulation-based modelling and performance analysis of the PFS algorithm in the context of cross-layer design for wireless mesh networks, such as MEMBRANE.

As the first step into the study of PFS in wireless mesh, we assume each node has enough transmit antennas and SIMO is used for the communication between two nodes. This assumption could be relaxed when there is cooperation among nodes. Frequency-reuse can also be used to reduce the number of neighbours to eliminate the need for large number of transmit antennas per node. Another research direction is to introduce proportional fairness in allocating sub-channels to different nodes, i.e., extending the research from single-carrier to multi-carrier.

The derived joint scheduling and QoS routing scheme – a cross-layer scheme – has been proven able to guarantee multi-constrain QoS to a wide range of applications while at the same time exploit the multi-user diversity gain. This framework covers and successfully combines aspects from several layers (i.e., from PHY to Application) and is expected to be highly beneficial to any wireless backhaul mesh network such as MEMBRANE. While only throughput, delay and packet error rate have been considered as QoS performance metrics in our analysis, several other metrics can be easily included (such as delay jitter or user-defined utilities). Further research may include the investigation of the joint QoS routing and scheduling optimization problem using different directional antennas and MIMO techniques in the PHY layer.

The proposed QoS MIMO routing algorithm can be easily applied to any multi-hop system of wireless MIMO transceivers. Our simulation results have shown that the proposed scheme, while simple to be implemented, it can provide significant benefits to a system by increasing the network throughput while at the same time can guarantee the required QoS to the overlying applications. However, further improvements and better understanding of this algorithm can be achieved by releasing and/or altering some of interference assumptions and fine-tuning the system parameters.

4.4 Wireless multi-hop backhaul IP network design

Analyzing the results provided by the integrated simulator, some considerations for network configuration and deployment can be drawn.

Table 1 shows a synthesis of some of the obtained results with the integrated simulator. It shows for different scenarios, characterized by the number of concurrent active TCP flows and the average number of hops between the source and the destination, the maximum achieved goodput, the average PER and the average packet delay.

Table 1 - Synthesis of some of the obtained results with the integrated simulator.

Scenarios	Goodput	PER	Average packet delay
1 flow - 3 hops	10 Mbit/s	~ 0	~ 0.01 s
1 flow - 5 hops	3.5 Mbit/s	~ 0.01-0.001	~ 0.02 s
3 flows - 3 hops	7.5 Mbit/s	~ 10-5	~ 0.01 s
3 flows - 5 hops	3 Mbits/s	~ 0.01-0.001	~ 0.03 s
6 flows - 3 hops	4 Mbit/s	~ 10-5	~ 0.01 s
6 flows - 5 hops	1.4 Mbit/s	~ 0.01	~ 0.1 s

Obtained results confirm the, somewhat obvious, behaviour that increasing the number of active flows in the network worsen achievable performance (in terms of goodput and average packet delay), because network resources must be shared among more flows and also interference grows in the network.

Simulation results show that the achievable performance depends also from the average number of hops from source to destination. For example, when the average number of hops increases from three to five, goodput strongly decreases, even in the case there is only one active TCP flow. This behaviour is confirmed by the measured PER that greatly increase when the average path length goes from 3 to 5 hops. Also the average per packet delay increase when the number of average hops goes from 3 to 5.

Obtained simulation results show that achievable performance (goodput and average per packet delay) depends more on the average number of hops than on the concurrent number of active traffic flows. This primarily depends on the interference level in the network that strongly grows as more nodes are transmitting concurrently when path length increase.

Our distributed opportunistic MAC algorithm, in fact, allows multiple nodes along a path to simultaneously transmit (after final decisions on who transmit and who receive have been taken and exchanged among all neighbouring nodes). This increase network performance but also increase the amount of interference in the network: each node on a path generates interference that can be caught up by the other nodes of the path, especially the closer ones. This is why also in the case of a single path, increasing the number of hopes of the path will worsen the achievable performance.

Another contributor to the interference in the network is the adopted adaptive modulation scheme that tends to use high spectral efficient modulations (16 QAM, 64 QAM) when possible. High spectral efficient modulations, however, require stronger power levels and therefore increase the interference level. Moreover, the adopted large system bandwidth (50 MHz) contributes in making MEMBRANE nodes picking up more interference.

Future research directions are envisioned in activities for studying, developing and evaluating potential performance improvements for the MEMBRANE network.

We have seen that interference limits achievable performance, one promising approach would be to tackle or reduce interference level in the network.

One possibility is the adoption of smart antennas. Currently we are using beamsteering antennas in the integrated simulator. The adoption of smart antennas, instead, would compensate interference and therefore allow better performance at TCP level in MEMBRANE network.

Another possibility is the adoption of a power control algorithm that would manage the power transmitted by each node, which would help in controlling the interference level and therefore improving performance.

Another possibility would be the design of an “interference aware TCP”, that is a new TCP protocol that would use the information coming from the link layer about the current interference level for deciding about its congestion control and recovery procedures.

Buffer size is another important parameter to take into consideration: its value influences the scheduler performance. When the buffer size is increased the scheduler can better exploit the channel condition and offer to TCP better channels. Obviously, an increase in the buffer size requires an increase in nodes complexity, particularly considering that a buffer is needed for each traffic queue in the node. A detailed study about the trade-off of different buffer sizes could be beneficial for performance improvement.

4.5 MEMBRANE system simulator

Investigation of the relaying mode selection technique in the MEMBRANE network has shown that careful intelligent selection of the relaying modes for transmissions of each Access Nodes allows improving the aggregate network throughput considerably (up to 2.5 times). The main performance improvement comes from the simultaneous transmissions of different network nodes that enable reuse of the spectrum resources between them. Therefore we can conclude that multi-hop transmission of the data between the network nodes has big advantages over direct transmissions between the End Node and the Access Nodes provided that efficient scheduling and routing algorithms are used.

For the wireless networks implemented above the average rooftop level steerable directional antennas provide considerable performance improvement and therefore may be recommended to enhance the network performance. In this respect even simple six-sector antennas with switched beams are capable increasing the network throughput up to 4 times as opposed to omnidirectional antennas.

For the wireless network implemented below rooftop directional antennas do not provide considerable throughput improvement due to rich multi-path propagation and lack of distinct direction of signal propagation between the network nodes. For such networks use of adaptive antenna arrays at the nodes may be recommended since they provide considerably better throughput enhancement. For example 12-element antenna arrays provide 6-10 times throughput improvement over omnidirectional antennas, the improvement occurring not only for individual links, but also for the entire wireless network.

Adaptive antenna arrays may also give considerable throughput improvement for the ART network (6-7 times for 12-element antennas). When using multi-carrier signal in ART networks the equal beamforming coefficients may be applied for all subcarriers, which considerably reduces the amount of computations needed to adjust the antenna system. Because of relatively frequency-flat channels in the ART propagation doing such a unified beamforming does not cause performance degradation of the network and therefore may be recommended. For the BRT propagation characterized by highly frequency-selective channels between the network nodes more flexible per-subcarrier beamforming improves the network throughput up to 1.5 times over rough beamforming and therefore is recommended for implementation in such networks.

Based on the simulation results we may not recommend using cooperative relaying techniques as well as phased antenna arrays, due to lack of the network throughput performance improvement over simpler techniques. In this respect performance of the cooperative relaying modes may be achieved with the help of intelligent selection of the division and simultaneous relaying modes. Performance improvement due to use of the phased antenna arrays may be achieved with the help of simpler sectored antennas or with the help of adaptive arrays with less than half elements.

In the MEMBRANE project we investigated influence of different intelligent antenna techniques onto the network performance. In this regard we used optimisation of the antenna patterns taking into account the information about only single link. Further investigation may include more complex optimisation task of joint TX/RX beamforming optimisation for several network nodes with constraints on the required QoS level. Further level of optimisation may include all TX/RX beamforming, routing and scheduling control together.

In the MEMBRANE project new results on the network throughput performance and other metrics have been obtained for centralized and distributed approach for control of the resource allocation. However, these two approaches have been investigated independently. In this respect, the interesting question for further investigation is the choice of the scheduling approach depending on the number of nodes and the geographical size of the MEMBRANE network.

4.6 MEMBRANE Demonstrator

From the work carried out for the development of the demonstrator work, a certain number of recommendations on future design of MEMBRANE nodes can be issued assuming that the MEMBRANE system is capable to operate in two distinct modes: a centralized one using the DSA algorithm and a de-centralized mode employing the MDS protocol. The recommendations concern the implementation aspects of the algorithms in wireless backhaul nodes of a MEMBRANE system.

4.6.1 MEMBRANE System using DSA

The design, development and implementation of the MEMBRANE PHY Demonstrator has produced significant insight of the Data Splitting Algorithm (DSA) that result on several interesting recommendations regarding the design of nodes for the MEMBRANE wireless broadband backhaul network.

Based on the fact that the current wireless broadband technology is based on well-established IEEE 802.16d/e and IEEE 802.11n OFDM(A) systems, we have noticed that the application of the DSA algorithm does not require any significant alterations to the current transmission chains besides the implementation of the modules in charge of the antenna weight vectors calculation and their application to different transmitted data streams.

Spatial multiplexing modes and multiple antenna techniques are currently supported by the IEEE standards of wireless broadband systems. Several commercial transceivers are currently starting to include the Singular Value Decomposition (SVD) calculation for the implementation of the closed loop MIMO systems. Efficient hardware implementations for the open loop and closed loop MIMO systems are present. Since in the implementation of the DSA, the calculation of the antenna weight vectors is a standard procedure carried out by the SVD block, we can conclude that currently available SVD hardware can be easily reused in the integration of the DSA algorithm. A similar reasoning can be applied for the module(s) that applies the weight vectors to the transmitted and received signals. Hence, the implementation of the DSA algorithm can be a very effective way to enhance the performances of the wireless backhaul network. The implementation of the DSA does not require development of any dedicated signal processing blocks but instead only requires the modification of the signal processing functions available in the modern wireless communication transceivers.

4.6.2 MEMBRANE System using MDS

From the implementation and evaluation of the one-round MEMBRANE Distributed Scheduler (MDS) several recommendations concerning its integration into current wireless backhaul networks can be produced. The MDS protocol has demonstrate a relatively robust operational mode not easily influenced by synchronization errors and easily overcoming deadlock situations.

A first recommendation for the implementation of the MDS algorithm is that it is preferable to exploited into a meshed network where nodes have equal traffic needs. Near Base Stations (BS) or End-Nodes (EN), the flow tends to have single direction and the algorithm does not provide any fairness concerning the distribution of bandwidth to the nodes.

Another recommendation for MEMBRANE nodes is that besides the implementation of different options of large data sequences, thoughtful processing that avoids interruption procedure should be considered. In fact, the load of additional nodes can be mitigated by a judicious selection of the length/duration of the data part. Additionally, the size of the control packets exchanged only marginally affects the operational mode of MDS. Thus, if and when additional control information is required, it can be conveyed with relatively minor effect on the network operation. Furthermore, it is clearly depicted that the algorithm's performance benefits substantially from large packets as opposed to constrained. Thus, it is recommended to use the maximum size of data packets that the network supports. Hence, only interruption to the algorithm flow can significantly affect the overall performances.

It is also recommended to exploit the advantages of distributed scheduling by joining the MDS scheduling decisions with routing and congestion control rules. The MDS algorithm behaves better when the higher layer protocol is connection oriented and uses some sort of congestion control mechanism such as TCP.

From a complexity point of view, it is recommended to install the scheduling procedure in the centre of the control entities of the nodes and to assign a processing mode with relatively high priority. Judicious triggering mechanisms and memory management can reduce the processing time which is the main reason of extra delays produced by the MDS algorithm.

Concerning the evolution to the two-round version of the algorithm, it is recommended to insert the information about the second ring of neighbours in a compress manner to minimize the length of the mini-slots and to insert this additional information in such manner that any possible interruptions are minimized during the scheduling process of the algorithm. It is expected to have a much higher efficiency by the two-round scheduler.

Finally, concerning the memory required to support MDS, if the number of stations remain relatively small, no excess additional memory is required in contrast to large networks where the maintained vectors and matrixes may require additional memory. The footprint of the code is actually relatively small. However, any additional memory can always be proven valuable for matrix/vectors manipulations.

4.6.3 Future Research Directions

The successful development of two MEMBRANE Demonstrators and the integration of two complementary algorithms/protocols issued from research carried in different activities of the project demonstrate the constructive cooperation and coordination among the consortium. Thanks to this valuable interaction, the integration difficulties have been surmounted. In addition, the development of two prototypes shows that the consortium is flexible and able to enhance the framework of the prototyping work in order to cover additional research area and complete the objectives of the project.

The prototyping activity and the constructed hardware platforms can be further exploited either in future research projects such as MEMBRANE or for the evaluation of techniques relative to in-house activities. A possible initial research direction could be the enhancement of the prototypes with the integration of add-ons capabilities to the selected algorithms. For example, the implementation of the second-hop version of the MDS algorithm and/or joint processing with routing decisions and transport layer cross-layer information could be considered. The developed hardware link level emulator (HLLE) can be integrated into the system level simulators to be used instead of the PHY abstraction mechanism to increase the accuracy and the reliability of the system level performance evaluation of the modern OFDMA wireless communication systems [Mal08b]. Finally, a more advanced integration of the algorithms into currently available wireless systems could also be investigated. In this case, the repercussions of the demonstrated techniques into features of the system not investigated in MEMBRANE such as mobility support and resource management could be studied.

5 Concluding remarks

In this final report we presented a comprehensive summary of the motivation, technical objectives and challenges in the design of a highly efficient multi-antenna multihop wireless backhaul and described the approach followed in the course of the MEMBRANE studies. We then discussed the innovative concepts and ideas, the algorithms and system architectures and the methodologies and software and hardware tools developed in order to address the technical objectives and challenges and assess the resulting performance benefits. One of the main goals of this report was to also present, along with the performance improvement, the underlying tradeoffs and complexity considerations and provide recommendations for future deployment of MEMBRANE systems and suggestions for promising/critical research directions in this area.

The framework of the MEMBRANE studies proved to have provided a fertile ground for strengthening and expanding the theoretical understanding of multi-antenna, multihop wireless networks and for the development of novel concepts and cross-layer architectures, such as the combination of the spatial and relay degrees of freedom in a single transceiver algorithm, the joint optimisation of scheduling, routing and power control among others. It has also given the opportunity to the participating organisations to develop simulation tools and the MEMBRANE prototype that will be valuable research and technology evaluation platforms beyond the completion of the project. Most importantly, it encouraged knowledge and expertise exchange among the participants, especially in view of the cross-layer approach followed and while addressing the requirements of the software and hardware platforms design, and allowed the investigation of new technologies with potential for future exploitation.

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[MEM D4.2.2] IST-MEMBRANE, Deliverable 4.2.2, "Performance studies of the new routing, scheduling and power control algorithms by simulation and/or mathematical analysis"

[MEM D5.1.1] IST-MEMBRANE, Deliverable 5.1.1, "Comprehensive PHY layer model and performance analysis of the PHY link for different scenarios"

[MEM D5.1.2] IST-MEMBRANE, Deliverable 5.1.2, "PHY abstraction methodology and SLS simulator implementation"

[MEM D5.1.3] IST-MEMBRANE, Deliverable 5.1.3, "System level performance analysis"

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7 Annex A: Publications

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2. Cemal Akcaba, Patrick Kuppinger and Helmut Bölcskei, “Distributed Transmit Diversity in Relay Networks”,Information Theory Workshop (ITW), July 2007.
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4. A.M.Kuzminskiy, Y.I.Abramovich, “Interval-based maximum likelihood benchmark for adaptive second-order asynchronous CCI cancellation,” in Proc. ICASSP, Honolulu, Apr. 2007.
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8 Annex B: Standards contributions and invention submissions

Standards

1. IEEE 802.16 Broadband Wireless Access Working Group: [C802.16m-08/1186r2] “Proposal for Relay Evaluation Methodology,” (Jerry Sydir, Alexander Maltsev, Andrey Pudeyev, Andrey Chervyakov, Vadim Sergeyev, Alexey Khoryaev, Alexei Davydov) - Adopted in the evaluation methodology of the 802.16m standard.
2. IEEE 802.16 Broadband Wireless Access Working Group: [C802.16m-08/1393] “Relaying Mode Selection Proposal for IEEE 802.16m,” (Alexander Maltsev, Vadim Sergeyev, Andrey Pudeyev, Jerry Sydir, Alexei Davydov, Alexander Maltsev Jr.) – Submitted.
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