

MEMBRANE: Multi-Element Multihop Backhaul Reconfigurable Antenna Network

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Abstract— The ongoing proliferation of wireless broadband data services is expected to lead to increased demand on the backhaul networks. The typical upgrade of wired lines to high-speed fibre networks is not always an available or economically attractive solution. In such cases, as well as in cases where no wired infrastructure is available, wireless approaches could offer an appealing alternative.

In the IST-MEMBRANE project the design of reconfigurable multi-antenna, multihop wireless backhaul networks is proposed 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 all users, including those in less developed, peripheral and rural areas. In order to provide cost-efficient wireless backhaul the proposed approach relies on an adaptive, multihop (mesh) networking design that makes use of channel state information and interference optimized resource allocation and routing. The potential performance gains will be assessed through theoretical studies, simulations and proof-of-concept prototyping and demonstration.

Index Terms—backhaul, multi-antenna, multihop, broadband wireless network

I. INTRODUCTION

THE ongoing proliferation of wireless broadband data services is expected to lead to increased needs on the side of the backhaul network, which transports data between the access network and the wired Internet, as well. The typical upgrade of wired lines to high-speed fibre networks is not always an available or economically attractive solution. In such cases, wireless alternatives could offer an appealing alternative. We propose 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 are the following:

Clusters of access points: the wired infrastructure in use at this time to support the second and third generation cellular networks is *ill suited to support clusters of high-speed wireless*

access points (APs) employing new technologies such as IEEE802.11 a/b/g/n/s and IEEE802.16-2004/e. A typical backhaul network today consists of copper wires running at E1 (2.048 Mbps) or E3 (34.368 Mbps) rates. The conventional upgrading to high-speed fibre connections is indeed taking place in many locations. However, this upgrading is a costly and time-consuming undertaking. The process involves obtaining rights of way, laying and activating the fibre. The optical terminal equipment is still expensive. Moreover, today's wired backhaul networks are mostly controlled by the incumbent local exchange carriers (ILECs), who own the lines. This constitutes a high barrier of entry for competitive local exchange carriers (CLECs), utility companies or others who might want to provide high-speed data access to consumers. Options in the local carrier sector are still scarce, therefore limited competition is in place constituting a factor of rigidity and over costs in the deployment of new access technologies. The current difficulties in new lines deployment due to the increased regulations by local authorities, makes the task of backhaul especially costly and time-consuming.

3G Picocells: as wireless data demand keeps growing, 3G cells tend to shrink, in order to satisfy the capacity demand. In cases where fibre is not readily available (such as in several countries in the recently enlarged EU), *the cost of leasing an E3 line* (since E1 will likely not satisfy the data demand of a 3-sector HSDPA cell) *may be prohibitive for the operator.* This is more so the case for small operators that deploy, for example only in dense urban areas, such as city centres. Wireless backhaul would again constitute a faster-to-deploy or cheaper alternative.

Remote areas: wireless data services are a social good that is especially needed in remote and isolated areas, or regions under development, that have a poor wired network infrastructure. While wireless data access technologies can make up to a large extent for the lack of wired access, these can be only offered if accompanied by an accordingly sized backhaul network. It is not only doubtful that the required investment for bringing cable and/or fibre will ever pay for itself in such remote communities but, more importantly, such an undertaking will probably take several years, *thus stalling progress and depriving from the benefits of broadband data access the very communities that need it the most.* Moreover, corporate facilities and plants are often built in remote areas; these too

could benefit from a wireless broadband backhaul whenever wireline solutions of comparable bandwidth are not available.

Given the above-described need for an efficient wireless backhaul network, its successful deployment necessitates careful design and this is likely to require nothing short of a number of technological breakthroughs. The main envisioned requirements of such backhaul network are the following:

Quality of Service:

- Throughput performance: in order to satisfy the growing demands of data throughput of wireless access networks (both 3rd generation and 802.XX), a primary target of the corresponding backhaul network is its high capacity.
- Delay performance: several applications (such as push-to-talk/push-to-view, video-conferencing, remote medical assistance applications, on-line gaming, etc.) have stringent delay requirements whose satisfaction is critical to acceptable user experience. Clearly a wireless backhaul network, despite its topology, must meet these requirements.
- Coverage: especially in the case of remote or isolated areas, it is important that the backhaul network has enough range to reach the end nodes, despite natural obstacles and the lack of wired infrastructure.
- Overall capacity: obviously, while providing performance and coverage, being a wireless network, such a backhaul has to be able to provide sufficient capacity from a system point of view (to be able to serve the backhaul traffic load of an ample area under cost-effective principles).

Reconfigurability: another important feature of wireless networks is that they must be capable of reconfiguring themselves, in terms of network topology, traffic flow and propagation conditions. For example, one could imagine the frequent addition of new nodes in the first phases of deployment. The network should be able of reconfiguring its traffic flow in a large time scale as the node topology changes. In a shorter time scale, it should be able of adapting to traffic patterns that change with the time of day; an even higher degree of resolution would require reconfigurability of routing and scheduling.

Heterogeneity: since wireless broadband access networks employ several technologies, it is important that the proposed backhaul network is capable of matching these heterogeneous networks. Ideally, the backhaul should work in an agnostic way with respect to the employed access technology. From a more practical perspective, this agnosticism will need to trade-off with cost, technology complexity and deployment efficiency.

Ubiquity: seen from the point of view of society as a whole, it is not acceptable to deliver wireless broadband services only in areas where the wireline upgrades of the backhaul network are economically and logistically viable. On the contrary, the society imperative is to make such services available equally fast to all areas. The addition of efficient wireless backhaul in the portfolio of available backhaul solutions will go a long way in ensuring the delivery of wireless broadband access to the entire addressable population in a ubiquitous manner.

Openness: from the operator's point of view, it is important that the developed concepts meet the requirements of double-openness, i.e., standard interfaces and multi-supplier technologies. On one hand, the openness enables us to design

backhauling as a commodity from a variety of technological options (wired, wireless), which hide the underlying technicalities, thanks to the existence of standardised interfacing concepts. On the other hand, the openness also ensures the capacity of implementing a technology that is continuously improved by a large number of infrastructure providers.

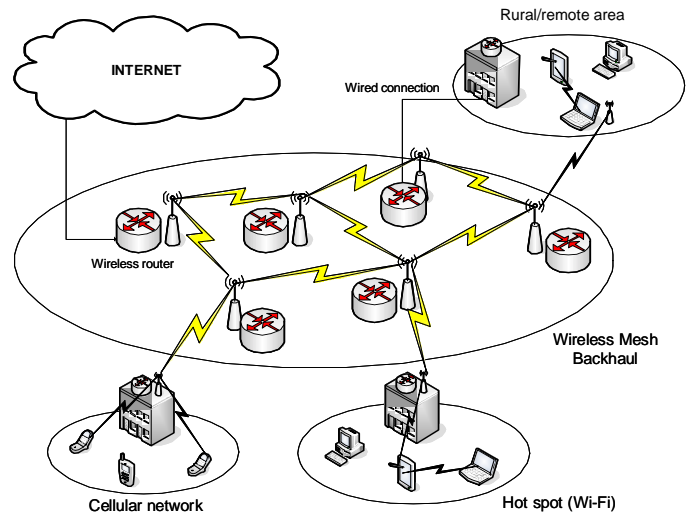


Fig. 1. MEMBRANE Wireless Mesh Reference Architecture

II. TECHNICAL APPROACH

The backhaul network must meet a number of technical requirements: it must meet the *capacity* needs of its Access Nodes (ANs); it must meet the *delay* requirements of the end user applications; it must provide a large enough effective *range* to ensure that each AN can reach the End Node (EN). Moreover, additional requirements should be imposed that eventually aim at a low-cost and environment-friendly network architecture. In particular, it is envisioned that the Intermediate Nodes (INs) are mostly mounted on low-to-moderate heights (on the order of 3-10m, for example mounted on electrical or telephone poles) and operating at low powers (on the order of at most a few Watts). As such, the connections on a given route between an AN and the EN will not necessarily be guaranteed a direct Line of Sight (LOS). Moreover, different links on this route may have very different propagation characteristics (for example, the last link (“hop”) to the EN point may typically enjoy a much smaller angle spread than the intermediate hops).

To satisfy the above requirements, we will exploit a number of enabling technologies that have the potential, when combined, to deliver the expected performance. These technology enablers are: *Multi-hopping*, *Intelligent Antennas* and *Opportunistic routing & scheduling*.

Multi-hopping, i.e. the use of relays between the end user and the EN, is primarily motivated by the low power and the low heights of the access (AN) and relay (IN) nodes. Clearly, in low power transmissions, multi-hopping helps increase the *range* [1]. Moreover, since low height ANs are likely to be surrounded by several obstacles (buildings, cars, etc.), their LOS to the EN will be typically obstructed, thus making direct communication to the EN tower more difficult. Multi-hopping

helps avoid this problem via multiple links that are more likely to have a LOS between them.

Intelligent Antennas (IA) constitute another enabling technology that is particularly well suited to the MEMBRANE fixed wireless network architecture. The two most prevalent modes of use of intelligent antennas in point-to-point wireless links are beamforming (BF) and MIMO (sometimes referred to as spatial multiplexing) transmission (see [2]). Both approaches are appropriate in different types of propagation scenarios; for example BF is well suited to cases with narrow angle spread, such as in high towers; whereas MIMO is more appropriate in cases of rich electromagnetic scattering, such as in low-height links within the clutter. In both cases, BF or MIMO offer improved communication *throughput* and/or range. Moreover, through their added “spatial” degrees of freedom, they can also reduce the interference from adjacent links. A more modern view of IA is that BF/MIMO hybrids can be designed that match in the best possible way a given propagation environment (called reconfigurable IA techniques [3]) or/and exploit channel state or other cross layer information [4]. Given the different types of propagation environments that are expected in MEMBRANE, reconfigurable and cross layer optimized IA techniques are expected to *boost throughput performance* and reduce interference and delay, thus improving overall end-to-end performance.

The combination of multi-hopping with multiple (intelligent) antennas is a field that is virtually unexplored and it will constitute a major placeholder for innovation in MEMBRANE. There is hope that the combination of these two technologies can help boost network capacity and achieve the target quality of service. This is still not well understood in theory, but some preliminary evidence is indicative of the potential of the combined technology.

Opportunistic routing & scheduling is another important enabling technology for the efficient design of the wireless backhaul and targets primarily the satisfaction of the network’s *delay* requirements; when combined with IA it can also increase the end-to-end throughput, as explained later. By opportunistic routing and scheduling we refer to routing and scheduling policies that take into account the *network context*. By this we mean the quality of different links, the data traffic needs on different ANs, the capacity of different relays, the packet activity of different links, etc. Another term sometimes used is “*reconfigurable*” routing and scheduling, which reflects the fact that the employed algorithms reconfigure routing and scheduling according to the network needs. Since the mesh structure of multihop networks tends to increase end-to-end delay, we believe that intelligent routing and packet scheduling can recover this potential delay loss.

For example, opportunistic routing could take advantage of the fact that in a wireless network transmitted packets may be heard by multiple neighbours at the radio level. Instead of choosing a single route ahead of time, opportunistic routing would determine the path as the packet moves through the network. Preliminary simulations of a specific technique suggest that there are cases where opportunistic routing may be able to increase throughput by a factor of two compared to ordinary unicast routing [5]. Again, in MEMBRANE we will

try to understand the fundamental limits of opportunistic routing / scheduling on the delay of mesh networks and will propose realistic algorithms that try to get as close as possible to these limits.

Another potential gain of multi-antenna multihop mesh networks is their potential for *significantly improved QoS via combined opportunistic routing and spatial data multiplexing*. Opportunistic scheduling can offer further gains, even in the absence of intelligent antennas. It is expected that, when combined with opportunistic routing, the gains are enhanced further. For example, beams can be “switched” on and off in an opportunistic fashion, in order to minimize interference between neighbouring nodes.

The key technical areas are outlined in the following paragraphs.

I. Theoretical multihop network performance analysis

In order to carry out a theoretical performance analysis, a framework will be first developed to derive *capacity scaling laws* (in the limit of a large number of nodes) of MIMO multihop relay networks, and to assess *how fast* (in terms of the total number of nodes in the network) the network capacity of a *finite network* converges to this asymptotic limit by using large deviation theory [6]. The resulting framework will also yield insights into the impact of large-scale fading, path loss, amount of channel state information, synchronisation accuracy, and channel bandwidth on the overall network capacity.

This framework shall be used to assess the performance of different network signalling (routing and scheduling as well as space-time processing) strategies, in terms of network capacity. These findings will provide insight into the question of *capacity-optimum signalling strategies*. In particular by applying this approach the impact of opportunistic routing and scheduling on network capacity will be assessed. Moreover, by devising a signal-space formulation of the capacity scaling problem and having different nodes use only a subset of the available signal space dimensions, the inclusion of traffic models will be explored.

II. Multi-antenna link signalling

Adaptive antenna techniques, such as MIMO transceivers, space-time coding, interference mitigation and cross-layered optimized array processing will be considered in this context of the multi-antenna studies. Basic assumptions about the physical layer, considering feasibility and relevance to current technological trends, will include licensed spectrum bands in the 2–11GHz range, air interface based on OFDM multiplexing.

IA/MIMO transceiver algorithms will be performed for different propagation scenarios (Pole-to-Pole & Pole-to-High Tower) different antenna configurations and different LOS conditions. The selection of suitable antenna array systems for each of the wireless backhaul links will be based on different types of propagation channels associated with the geographic terrain wherein the radio network operates. Based on these considerations suitable antenna array topologies for different types of nodes and directions of communications will be identified. The novel IA algorithms to be developed will be *reconfigurable* to different propagation environments and

network topologies, e.g. due to the addition of new nodes (especially in the early stages of deployment) and / or the failure of existing nodes. Furthermore, the issue of interference between adjacent links will be addressed and IA algorithms for efficient interference mitigation will be devised.

The design of the IA/MIMO-enabled scheduling and routing schemes will further exploit the spatial dimension, such as adaptive beams, as a new routing resource. These IA/MIMO-enhanced routing techniques will be reconfigurable in terms of traffic conditions, router capacities and QoS constraints, allowing for optimised system dimensioning and network topology. The design of the IA/MIMO-enabled scheduling and routing schemes will take into account the conclusions of the theoretical multihop network performance analysis with regards to spacing guidelines between relay nodes and the modelling and mitigation of interference in order to provide reasonable frequency reuse patterns.

III. Routing, scheduling and power control

In order to achieve the best network QoS for the proposed wireless backhaul network architecture several key link and networking issues need to be addressed, such as radio resource allocation, routing and power control. These will be guided by capacity bounds derived in the theoretical multihop network studies and the delay requirements specified at the IP network level, as commanded by end user applications and IP protocol design. Input from the theoretical multihop network studies and the multi-antenna studies will be used in terms of antenna configurations, channel models, number of hops and frequency reuse, in order to provide the network context. The outputs of this study will be radio resource management algorithms designed at the MAC level; antenna-aided jointly optimized opportunistic routing and scheduling algorithms for the considered wireless mesh networks; as well as power control policies for efficient resource utilization.

Efficient radio resource management: A key issue for the multi-cell network environments is inter-cell (or inter-base-station, inter-access-point) interference. At the physical layer, IA techniques to suppress interference will be applied. Resource management will be investigated for the considered networks at the MAC level. Efficient radio allocation algorithms can help improve the signal-to-interference-plus-noise ratio (SINR) significantly by avoiding co-channel interference from neighbouring cells. The added flexibility by the IA will enable more efficient delivery of data in order to meet stringent delay requirements of real-time traffic.

Jointly optimized routing and scheduling algorithms: It is known that routing and scheduling have been investigated individually in the literature. However, in MEMBRANE these issues will be investigated jointly [7] and design and optimization of the joint algorithms will be carried out in the considered multi-cell wireless environment. Using mathematical analysis and simulation, the joint algorithms will be evaluated for comparison with existing techniques and for gaining insights into the proper operations and identification of associated control parameters.

In particular, opportunistic routing and scheduling in the presence of data splitting will be considered. First, the impact

of data splitting (via beamforming) on the QoS of jointly optimised routing / scheduling algorithms will be investigated; and then the development of efficient opportunistic IA-based data splitting techniques will be explored, in order to improve end-to-end QoS.

Due to potential traffic concentration, it is expected that traffic forwarded from one node to the next one in the backhaul network would not be as bursty as that associated with individual terminals in cellular networks. As a result, the temporal correlation of co-channel interference in the backhaul network will be reasonably strong so that power control can and should be applied to provide additional performance gain [7]. To this end new power-control algorithms will be developed that are coupled well with the chosen radio-resource allocation and packet scheduling algorithms.

IV. Wireless multihop backhaul IP network design

To realize the potential merits of the multihop wireless backhaul network, not only advanced PHY techniques such as intelligent antennas need to be devised and employed, efficient design of higher layer protocols such as MAC and routing, and the overall network topology also require careful consideration. As for the transport layer, although several transport protocols have been developed for both wired and wireless networks currently there are no specific ones that address the characteristics of wireless mesh networks. We plan to investigate such transport protocols for the multi-hop wireless backhaul networks. The focus here is to examine the optimal cross-layer design for the MAC, routing and transport protocols.

In order to test scheduling, routing and transport algorithms, detailed network models of MEMBRANE scenarios will be implemented in some suitable network simulators. To analyze the capacity achieved by different solutions, especially the ones that combine opportunistic routing and spatial data multiplexing, realistic traffic models and QoS requirements are needed. Network topology, cell size and layout, access technology, propagation environment, antenna heights and configurations will follow from the identified MEMBRANE scenarios and will be used as inputs for network models implementation.

Overall network simulations will be fundamental in order to verify if developed algorithms meet defined technical requirements, such as end-to-end delay, capacity needs and coverage. Moreover, to test the adaptability of the developed opportunistic routing and scheduling algorithms to the changing network context, a set of different network models should be developed, each one with different parameters, such as quality of links, types of propagation channels (AN-to-IN, IN-to-IN and IN-to-EN), data traffic needs on different ANs, capacity of different relays, packet activity of different links, etc. Also, the addition of new nodes and the failure of existing nodes should be simulated and algorithms performance in these cases measured.

These studies will help the integration of the advanced MEMBRANE multi-element scheduling and routing features with the optimized transport protocol and the specification of the overall network.

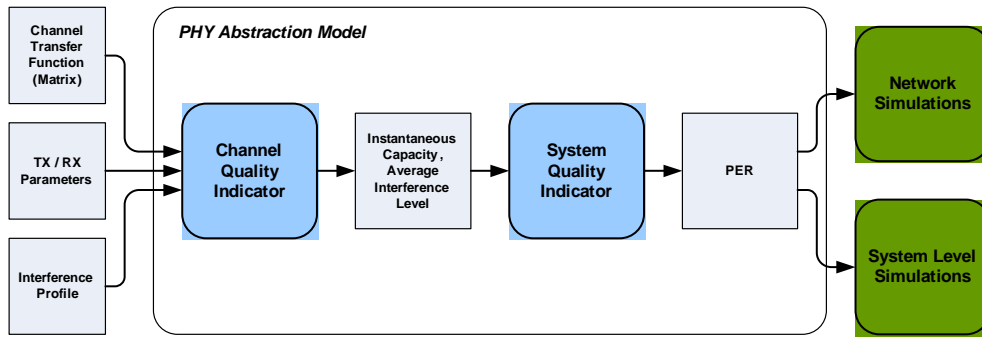


Fig. 2. Block diagram of the Physical Layer abstraction model

V. System simulation platform

In order to assess the performance at the link and system level of a wireless multi-hop backhaul network with reconfigurable IA/MIMO-enabled transceivers a simulation platform will be developed.

First, spatial channel modelling for multiple-antenna communication systems will be implemented, including ITU-A, B models and other models derived from the MEMBRANE scenarios. Then, a Link Level Simulator (LLS) will be developed for IEEE 802.16-2004 OFDM and 802.16e OFDMA physical layers, including multiple-antenna techniques, channel coding algorithms, acquisition and synchronization algorithms and different sub-channelization schemes.

Moreover, accurate physical layer (PHY) abstraction models will be formulated (Fig. 2), for different types of nodes and different scenarios in terms of channel models, co-channel interference and multiple antenna techniques used. Based on the channel and the PHY abstraction models, the design of a System Level Simulation (SLS) platform will be performed and high-level (coverage/capacity/spectral efficiency) performance analysis of multihop network will be carried out using the SLS simulator.

VI. MEMBRANE prototype

Under the MEMBRANE framework, a proof-of-concept prototype will be established to serve as a means to evaluate the concepts addressed. Specific features enabling the optimised backhaul network will be implemented in a commercial hardware platform and indicative demonstrator set-ups will be established, able to evaluate both the performance and the economic viability of the MEMBRANE network. Pre-existing modules for IEEE802.16-2004 OFDM based physical layer will be the starting point and appropriate module modifications will be carried out, in order to implement selected algorithms enabling diversity (MIMO and/or Adaptive antennas) techniques.

The main focus of the MEMBRANE prototype will be real-time PHY link establishment. Channel emulation for diversity schemes will be done either with an off-the-shelf analogue MIMO emulator operating in an IF frequency, or with baseband equivalent digitally generated impulse responses emulating the statistics of the channel environments under investigation. Implementation of a light version of MAC layer will be done in order to support the PHY on one hand, and on the other hand to roughly emulate the point-to-multipoint and mesh topologies

functionality in terms of (selected for implementation) advanced scheduling and resource allocation schemes, under predefined traffic and channel scenarios.

The advanced techniques of the envisaged target MEMBRANE capacity optimised multihop backhauling network will be proved by post-processing of the gathered results/statistics and visualized in a comprehensive way. The obtained results will be compared with the ones to be obtained by the System Level Simulator.

III. CONCLUSIONS

The IST-MEMBRANE project will design and study a novel wireless multihop multi-antenna network for the backhaul of wireless data networks. The overall evaluation of MEMBRANE's impact on the performance of the wireless backhaul will be carried out by assessing the enhancements achieved by the proposed multi-antenna enabled scheduling and routing schemes. Performance gains / behaviour will be evaluated via simulations at the link, MAC, network and at the system (multi-node) level and validated through over-the-air experiments.

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REFERENCES

- [1] D. Avidor, S. Mukherjee, "On the Probability Distribution of the Minimum Number of Hops between any Pair of Nodes in a Bounded Wireless Ad-Hoc Network Subject to Fading", IWWAN2005.
- [2] A. Paulraj, R. Nabar and D. Gore, Introduction to Space-Time Wireless Communications, Cambridge University Press, Cambridge, UK, 2003.
- [3] A. Alexiou, M. Haardt, "Smart Antenna Technologies for Future Wireless Systems," IEEE Communications Magazine, vol. 42, No. 9, pp. 90-97, Sept. 04.
- [4] D. Avidor, J. Ling and C. Papadias, "Jointly Opportunistic Beamforming and Scheduling (JOBS) for Downlink Packet Access," Proc. of IEEE ICC, June 2004.
- [5] S. Binwas and R. Morris, "Opportunistic routing in multihop wireless networks," Proc. HotNets II Workshop, Nov. 2003.
- [6] A. Dembo and O. Zeitouni, "Large deviations techniques and applications" Jones and Bartlett, Boston, 1993. Second edition, Springer, New York, 1998.
- [7] T.E. Klein, K.K. Leung and H. Zheng, "Enhanced Scheduling Algorithms for Improved TCP Performance in Wireless IP Networks," Proc. of IEEE Globecom 2004.
- [8] K.K. Leung, "Power Control by Interference Prediction for Broadband Wireless Packet Networks," IEEE Trans. on Wireless Communications, Vol. 1, No. 2, April 2002, pp. 256-265.