Flexible Relay Wireless OFDM-based Networks

Christian Hoymann[1], Panagiotis Dallas[2], Antonis Valkanas[2], Jeremy Gosteau[3], Dominique Noguet[4], Reza Hoshyar[5]

[1] RWTH Aachen University, Faculty 6, ComNets, Germany
[2] INTRACOM Telecom, Attika, Greece
[3] Motorola Labs, Paris, France
[4] CEA-LETI, Grenoble, France
[5] University of Surrey, Guildford, UK

***Abstract* — Providing diverse broadband services economically to everyone, even to subscribers in remote places is a major challenge for the telecommunication community. Broadband Wireless Access (BWA) is the most promising radio access technology to provide ubiquitous broadband access with performances similar to wired xDSL systems, which surpass current 3G mobile data rates. This paper addresses the challenges and solutions which will be investigated in the IST FIREWORKS project.**

FIREWORKS aims to improve the current BWA system IEEE 802.16 (WiMAX) by an enhanced multi-hop relaying deployment concept that utilizes ambitious smart antenna technologies such as space division multiple access (SDMA) or cooperative technology. By applying both future developments their individual advantages as well as synergy effects can be leveraged. Thus, the requirements regarding future telecommunication systems such as broadband QoS support, ubiquitous coverage, economic and scalable deployment can be provided by the resulting FIREWORKS system.

***Index Terms*—Multi-Hop, Relay, Smart Antennas, WiMAX, IEEE 802.16, FIREWORKS**

I. Introduction

IST - FIREWORKS [1] project aims to enhance OFDM-based wireless metropolitan area networks (MAN) with novel concepts such as flexible multi-hop relaying architecture and smart antenna radio communications with the final objective to design and specify a next generation Broadband Wireless Access (BWA) system whose capabilities are validated and demonstrated by a prototype. The competitive advantage of such novel BWA systems will be the ability for fast, scalable and cost-effective network deployment in highly diverse terrain environments and furthermore with considerably increased coverage and capacity capabilities. Telecom operators will benefit from reduced investment risks, higher scalability to customer expansion and provision of demanding but profitable services. End-users will enjoy ubiquitous access independently from the equipment nature or the communication environment. FIREWORKS comprises the utilization of novel network architectural elements (relay stations) jointly with a range of novel communication concepts that span from the physical layer (PHY) up to the Network layer. The core system operation is based on the optimization of the Medium Access Control (MAC) and Radio Resource Management functions through the novel prism of multi-hop architecture provided by means of relays. An additional impact also appears in the PHY enhancement of advanced antennas that allow for ambitious techniques such as space division multiple access (SDMA), spatial multiplexing, or cooperative communication. Considering the high correlation of the afore-mentioned methodologies a cross-layer optimization approach will be aimed at. An important aspect of the system design is the cost minimization, especially in the relay and subscriber station. Finally, the FIREWORKS prototype will provide sufficient insight for the evaluation of the economic viability of the relay based network concept and will also explore its environmental impact and its social acceptance.

The project has been initiated in January 2006, and will last two years. What this paper presents is the background of our studies and the solutions that we envisage to investigate in order to answer to the overall objectives. As such, no results can be found in this paper. On the contrary, the following sections analyze first the relay-based systems relevant to the project. Then, an interest is taken in the possible relay and cooperative protocols that can be applied at the MAC layer as enablers. Section IV focuses on the envisaged PHY solutions, whereas the last section presents the prototyping effort that will be initiated in order to validate the theoretical studies presented before.

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II. Relay-Based Wireless Broadband Systems

The traditional cellular point-to-multipoint deployment methodology is extended by relay-based multi-hop communication. Exploiting the advantages of relaying increases the system's capacity when the relays are placed within the coverage area of the base station (BS). Thus, highly shadowed urban environments and even outdoor-to-indoor scenarios can be covered. If the relays are placed on the cell border they extend the cell coverage. Like this broadband access can be provided to wide-area rural environments [2]. Figure 1 outlines a FIREWORKS deployment concept where two relays are placed at the cell border to extend the coverage (additional background circle) and to increase the capacity at the cell border to allow for indoor communication. Furthermore one of the relays provides coverage in an otherwise shadowed area. In order to optimally handle the novel relay-based deployment, optimized radio resource management (RRM) algorithms have to be designed. RRM might include space-time forwarding mechanisms to efficiently schedule spatially separated relays in SDMA. Enhanced PHY techniques such as cooperative communication or spatial multiplexing have to be selected and managed. If nodes, i.e., subscriber stations (SS) or relays become portable or even mobile, ad-hoc association and disassociation have to be addressed.

A. *Cellular Deployment Concepts*

The concept of flexible relay-based cell deployment distributes the high capacity available at the inner cell area (high-capacity PHY modes usable) into a capacity boost in the outer areas. Relaying functionality is provided either by ad-hoc enhanced (mobile, portable or fixed) SSs controlled by the customers or by fixed relays deployed by the network operator.

When evaluating the relay-based cell deployment it has to be compared to a conventional single hop deployment taking the coverage area into account. Diverse performance criteria consider different system aspects. Data rate and delay measures evaluate the capacity increase. The coverage area range of a relay enhanced BS shows the extension of the cell area. Calculating the capital expenditures (CAPEX) and operating expense (OPEX) of an operator exposes the economic potential of the developed system.

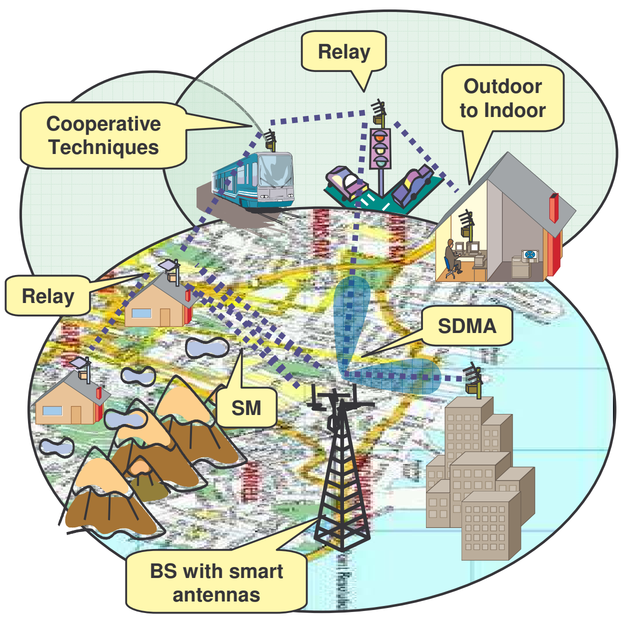

Figure 1: FIREWORKS deployment concepts

Adaptive antenna systems allow for simultaneous communication between stations. SDMA techniques can be used to simultaneously serve several relays by one single BS. The low mobility expected for relays in the infrastructure network privileges pre-distortion or joint detection techniques. Furthermore, different SSs might be scheduled in SDMA mode to be concurrently served by a BS or a relay. Relay and/or SSs sufficiently spaced might be served simultaneously.

Cooperative communication relies on several links established between one receiver (SS or relay) and different transmitters (base stations and/or relays). On one hand, transmitting the same signal via several independent links simultaneously increases the received signal strength by leveraging transmit and/or receive diversity techniques. On the other hand, transmitting independent signals simultaneously increases the throughput by means of spatial multiplexing. Finally, transmitting the same signal consecutively via different links decreases the bit error ratio of the decoded data. Thus, cooperative techniques might have a significant impact on the overall capacity of a relay-enhanced cell. Figure 1 shows a scenario where the BS is capable to either use spatial multiplexing (SM) or SDMA techniques.

Anyway, the control of such sophisticated radio techniques will have an impact on the design of RRM algorithms, on the specification of the MAC protocol, and the PHY techniques. Both relays may coordinate their transmissions in order to increase their service provisioning to the SS.

B. *Radio Resource Management Algorithms*

Exploiting the benefits of flexible relays and smart antennas will require the use of sophisticated radio resource management algorithms. The diverse usage of fixed, portable or mobile relays and the flexible application of novel deployment concepts will lead to individual RRM specially designed for each development. Potential RRM algorithms are introduced in the following.

End-to-end communications in relay-enhanced cells might involve several radio links in tandem. Provision of end-to-end quality of service (QoS) is an important aspect once commercial operators have rolled out their networks. QoS is the result of connection admission control, infrastructure design, and scheduling algorithms. Especially smart scheduling algorithms that are aware of the current link capacity are foreseen to have a significant impact.

Smart antenna technology requires individual resource management. For spatial multiplexing, data has to be scheduled for transmission on different antennas. Simultaneous and/or consecutive signal transmission on different devices has to be coordinated to leverage cooperative techniques. Finally, transmit diversity requires application of space-time codes that distribute the signal on different antenna elements. By exploiting the spatial domain to enhance the multi-hop communication, advanced space-time forwarding protocols and SDMA-aware scheduling algorithms will substantially increase the capacity.

The proposed relay-based deployment concept introduces unknown interference behaviour of co-channel cells. An optimization of frequency re-use patterns or sectors, specific mechanisms to coordinate neighbouring cells, and adaptive smart antenna techniques will have to be performed in order to optimally engineer the introduced interference.

The system's flexibility results from the ability of mobile, portable, and fixed SS to act as relays. Since these nodes might not be under the control of the operators, they associate and disassociate themselves and the relaying functionality is provided only in an ad-hoc manner. Thus, algorithms to manage the ad-hoc integration of nodes into the network infrastructure are necessary. New nodes that are entering the network should be self-configuring and the network should be optimized automatically. Finally, routing tables have to be updated by advanced algorithms after the self-configuration of the system.

C. Hybrid MAN and LAN Multi-Hop Networks

In hybrid local area network (LAN) and MAN deployment scenarios 802.11 access points [4] are connected to the 802.16 [5] relay-based network. This hybrid system allows legacy 802.11 terminals to connect to the FIREWORKS system. Hence, LAN access points of hot zones providing high capacity to a limited area could be served. The hot zones themselves could be deployed using relaying technology to benefit from the advantages of Mesh systems such as low cost, scalability, extended range and higher capacity.

Both LAN and MAN networks exhibit different benefits but have different requirements as well. From one side, the last wireless link to the customer could be provided by a LAN system fed by a MAN backbone. On the other hand, a LAN could extend the MAN backbone network by a flexible relay based deployment utilizing several hops. Thus, the switching point between the two relay-based systems is investigated. The actual balance between both systems will merely be topology and scenario dependent in order to optimize a certain set of criteria, namely: the cost, the flexibility, the capacity, and the QoS constraints for the requested traffic. Several solutions shall be studied in terms of standards and algorithms, based on existing or evolving proposals, such as IEEE 802.16 e/j for MAN and 802.11 s/n for LAN.

LAN and MAN can either operate on different or same frequency bands. If both systems operate in the same license-exempt spectrum, they have to coexist. To allow coexistence of the distributed wireless LAN and the centrally coordinated wireless MAN, a TDMA-based MAC frame structure (such as the one proposed in 802.16) has to be adopted. Furthermore, the transmission and reception phases of both systems must be coordinated under the control of the IEEE 802.16 MAC frame structure [3].

III. Relay-Based Medium Access Control Protocol

In order to control and manage the above mentioned enhancements an advanced MAC protocol has to be designed and specified. The MAC protocols that will be developed in the framework of the project intend to fully incorporate flexible relays operating with adaptive antenna techniques such as cooperative communication, SDMA [6] [7], transmit diversity and spatial multiplexing.

Flexible relays have an impact on the MAC layer. Key requirements of the MAC protocol are directly derived out of the deployment concepts. Adaptive antenna systems influence the MAC layer with respect to multi user capability (SDMA), higher throughput and/or increased received signal strength. Existing concepts and standardized solutions, especially IEEE 802.16e/j, the Mesh and the AAS option as well as IEEE 802.11s/n already includes some hooks to enable the protocol to cope with the introduced techniques. Still, additional protocol functionality has to be specified in order to overcome missing features and major drawbacks. The integration of both MAC developments, i.e., additional relaying functionality and advanced PHY techniques has to be performed jointly to benefit from the individual advantages as well as from the synergy effects. This will allow leveraging adaptive antenna techniques in the context of relaying such as “cooperative Mesh communication” and “forwarding in the spatial domain”.

Beside the MAC protocol an appropriate MAC/PHY interface need to be designed in order to interchange necessary information across these adjacent protocol layers. Thus, an enhanced specification of the PHY service access point will emerge.

The Mesh deployment concept relies on a number of relay stations per BS being deployed in the service area of the wireless system. Therefore, it appears to be extremely important to develop low-cost devices. Beside the standard extension, new MAC frame structures might be applicable to the existing standard [5] [2]. No or only minor additional functionality might be necessary and legacy devices might be used.

IV. Advanced PHY Techniques

One of the objectives of FIREWORKS is to investigate the potential of an MTMR cooperative relay-based system. Some of the features that FIREWORKS system will eventually contain are adaptive signal processing and MTMR spatial processing, and cooperative communication in the context of Mesh and relay-based deployment. In this context, cooperative multi-hop scenarios can be regarded as virtual antenna arrays, where each relay becomes part of a larger distributed array. This distributed quality naturally leads to a number of new challenges, such as design of optimal or close to optimal transmission and reception processing techniques for each involved node, formation of virtual MTMR link(s) by part or whole of the involved distributed nodes, use of appropriate distributed MTMR processing and coding techniques, transmit power allocation, identifying and establishing the required amount of synchronization and channel state information which will strongly depend on the type of deployed distributed MTMR technique.

Analysing and incorporating all possible efficient options into the system radically affects the design of the PHY layer. FIREWORKS system should be able to intelligently and dynamically identify the most advantageous communication scheme for the given scenario and composition of the relay and user terminals. This will only be possible by appropriate sharing of information among PHY and upper layers. This will allow the FIREWORKS system to choose an option that maintains efficiency of all the layers. The research and technological development of the PHY in FIREWORKS scenario is shown in Figure 2. It is based on a literature investigation on current multi-antenna systems [8] and their evolution towards possible cooperative coding [9].

Mesh topology, which is related to the cell deployment, affects only the Relay-based and the Cooperative type of development. In FIREWORKS, the PHY layer will be progressively extended to support additional technologies and techniques. Hence, the PHY layer will initially investigate well-known single user transmission techniques and select those that will be expanded to the multi user case. The next step will involve the application of relay functionalities to the PHY. Finally, cooperative capabilities will finalize the PHY development offering a flexible and modular component to the FIREWORKS system. In order to extend the PHY layer features to support cooperative communication, the PHY is structured differently in the FIREWORKS project. The PHY is perceived as a multi layer component. The basic layer mainly contains different MTMR techniques heavily addressed in the literature. MTMR techniques will complement each others within the FIREWORKS framework. In case of low mobility, Adaptive Modulation and Coding (AMC) techniques will be developed on the basis of MTMR schemes. AMC will exploit cases where good quality channel knowledge is known at the transmitter. Advanced antenna techniques and AMC will be appropriately incorporated in the PHY to maximize the system's efficiency. The set of MTMR techniques with AMC enhancement will form an Advanced Antenna System (AAS). In FIREWORKS, transformations from classical MTMR techniques to multi-user MTMR such as beam-forming and to AMC processing methods will be transparent. Relay, cooperative and multi user functionalities and transitions affect distinct layers of the PHY multi layer component.

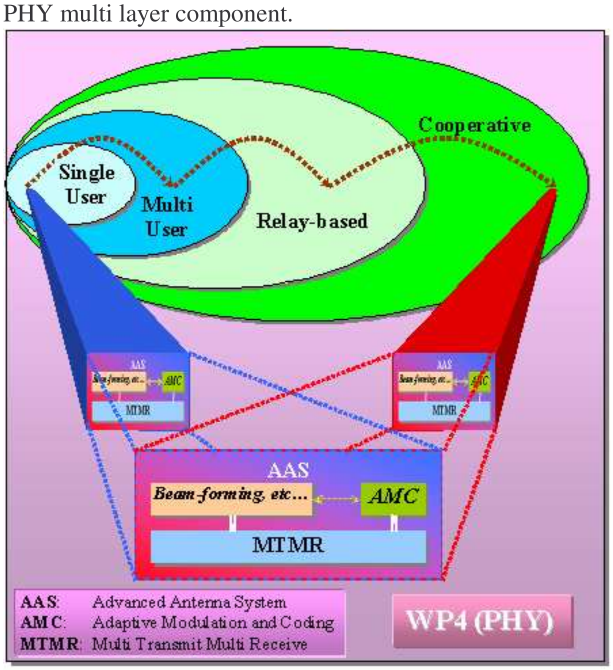

Figure 2: The PHY layer in FIREWORKS scenario

In FIREWORKS, particular investigation will be carried out on MTMR techniques for relay and cooperative communication. Basic characteristics and requirements of novel MTMR techniques will be extracted. Novel algorithms and judicious selection of metrics will be required in order to perform strategic selections that will improve the performance of tandem links. OFDM will be the waveform of choice due to its already proved and widely accepted capability to efficiently combat multi-path and demanding NLOS situations such as an outdoor to indoor link of a Mesh relay with a Mesh subscriber station.

V. Prototyping and Validation

In order to prove the potential of the FIREWORKS concepts, a deep analysis of the relay architecture will be carried out. The objective of this analysis is twofold.

First, the validation objective is to prove the technical feasibility of the relay based concept and more specifically their impact on the functionalities and complexity of the relays. To this end a comprehensive testbed based on prototypes connected through a Real-Time Advanced Antenna Radio Emulation (RTAARE) environment will establish the network of some relays contributing to the radio link. More specifically, the testbed will be used as a platform to validate selected MTMR scenarios of the FIREWORKS system.

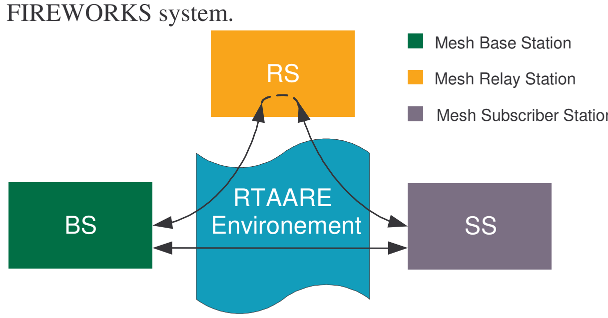

Figure 3: Simplified view of the testbed (here with 1 relay)

A new feature that is brought by the mesh nature of the FIREWORKS system in terms of MTMR techniques is the so called cooperative scenario in which several relays are used to bring diversity compared to a more classical MIMO approach. This technique requires specific scheduling algorithms and therefore, advanced MAC layer protocols able to support relay functionalities and cooperative communication will be evaluated as well. On the other hand the added value of using several antennas at the relay will also be analysed since it expected that some multiplexing techniques such as SDMA could be of great interest in the mesh context.

The RTAARE environment shown in Figure 3 provides a common and reliable framework to the integration and validation phases of the prototype establishment. It is an open architecture through which the advanced flexible PHY and MAC layer features of FIREWORKS will be demonstrated. The RTAARE environment includes a real-time channel emulator able to incorporate various impairments of the wireless medium.

Besides the proof of technical concepts, the FIREWORKS approach also has to be proven viable in terms of cost and acceptance. It is expected that several class of relays from low cost to high end will coexist in a FIREWOKS based deployed system. The potential low cost of relays makes us expect a dense deployment of devices, especially in urban environment because of severe channel conditions as well as to provide a better outdoor to indoor penetration that would make low cost plug and play CPE a reality. Therefore the hardware complexity of the relay including MAC, baseband, RF, and antennas will be analysed to estimate a potential cost of a relay and its impact on the cost of other features of the system.

This scenario also means that societal acceptance of the relay concept is important. One of the major challenges there is to prove that the relays can have a form factor that enables them to be hidden in many situations. The size of the relay is mainly driven by antenna size and power supply. The antennas for the relays will be analysed and small size antennas will be designed to quantify the size or the target relay. Another key element is to prove that compared to a base station infrastructure, people will not be more exposed to electromagnetic fields. To that respect, it is expected that the use of directive antennas and/or MIMO techniques will enable an optimization of the transmitted power.

VI. Conclusion

The foreseen FIREWORKS system will be able, when completed i) to flexibly adapt to the customers' ubiquitous broadband access and operators' demands, e.g., economic roll-out and operation and ii) to react to internal or external variations. These challenges are overcome by the novel relay-based deployment and by innovative smart antenna techniques.

The resulting wireless metropolitan area network with multi-hop capability that leverages smart antenna techniques can provide ubiquitous radio coverage under challenging environmental conditions, achieve high QoS requirements, reduce interference and allow for efficient frequency re-use. Furthermore, it can be economically deployed and operated, and it flexibly adapts to changing users' behaviour or environmental conditions. Further work is therefore to be expected in the following months in order to assess these assumptions with theoretical results and with a testbed.

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