The FIREWORKS Project: FlexIble REIay Wireless OFDM(A)-based NetwoRKS

Ilias PANAYIOTOPOULOS[1], Antonis VALKANAS[1], Christos ANTONOPOULOS[1], Sebastian SIMOENS[2], Patrick ROSSON[3], Benedikt WOLZ[4], Reza HOSHYAR[5], Josep VIDAL[6], Robert BESTAK[7], Alberto MITTONI[8]

[1]*INTRACOM Telecom S.A., 19.7 Km New Road Peania-Markopoulo, 19002, GREECE*
Email: {ipan, abal, chra}@intracom.gr
[2]*Motorola Labs, Parc Les Algorithmes, Gif-sur-Yvette, 91193, FRANCE*
Email: simoens@motorola.com
[3]*CEA-Grenoble, 17 rue des Martyrs, 38054 Grenoble, FRANCE*
Email: patrick.rosson@cea.fr
[4]*RWTH Aachen, Templergraben 55, D-52056 Aachen, GERMANY*
Email: bmw@comnets.rwth-aachen.de
[5]*University of Surrey, Guildford, GU2 7XH, UNITED KINGDOM*
Email: R.Hoshyar@surrey.ac.uk
[6]*Universitat Politècnica de Catalunya, Jordi Girona 31, 08034 Barcelona, SPAIN*
Email: josep.vidal@upc.edu
[7]*Faculty of Electrical Engineering, Technicka 2, 16627 Praha 2, CZECH REPUBLIC*
Email: bestar1@fel.cvut.cz
[8]*WIND Telecomunicazioni S.p.A., Viadotto XXV Aprile, 9 - 10015 Ivrea TO, ITALY*
Email: alberto.mittoni@mail.wind.it

Abstract: The provision of economical ubiquitous Broadband Wireless Access (BWA) capable to achieve and surpass current 3G performances and throughputs even in remote locations experiencing severe propagation conditions can be achieved through the integration and deployment of relays that promise to enhance the system's capacity and coverage extension. The IST-FIREWORKS[1] project has been investigating improvements of WMAN and WLAN networks from enhanced multi-hop relaying deployments and through the exploitation of advanced techniques such as cooperative communication and novel distributed protocols. During the last two years, a conceptual study on issues related to relay-based deployment has been performed from which RRM algorithms have been identified. Design of novel MAC protocols and advanced PHY techniques to support such relay functionalities are been deduced. The aim of the paper is to introduce several of the major objectives and present some achievements of the project that due to paper length limitations represent only a small portion of the obtained results.

Keywords: Multi-hop, relay, cooperative communication, WMAN, WLAN, WiMAX, IEEE 802.16j, FIREWORKS.

[1] This work has been performed in the framework of the FP6 project FIREWORKS IST-027675 STP, which is funded by the European Community. The Authors would like to acknowledge the contributions of their colleagues from FIREWORKS Consortium (http://www.ist-fireworks.eu).

1. Introduction

IST - FIREWORKS [1] project aims to enhance OFDM(A)-based Wireless Metropolitan Area Networks (WMAN) and Wireless Local Area Networks (WLAN) technologies with novel concepts such as multi-hop architecture, flexible relaying deployment and cooperative communication with final objective to design and specify a next generation Broadband Wireless Access (BWA) system whose capabilities are validated and demonstrated by a prototype. Future BWA systems must have the ability for fast rollout, scalable and cost-effective network deployment in highly diverse propagation environments while exceeding current coverage and capacity capabilities. Some of the benefits for telecom operators are the reduced investment risks, the higher scalability to customer expansion and the provision of high and profitable QoS. End-users will enjoy ubiquitous access independent of propagation conditions and landscape variations. The introduction of Relay Stations (RS) into WMAN produces a significant increase of the link quality which leads to throughput enhancement and coverage extension. In FIREWORKS, the core system operation is based on the exploitation of advanced PHY techniques, the optimization of the Medium Access Control (MAC) and the design of novel Radio Resource Management (RRM) functions for the multi-hop architecture provided by means of relays. Finally, the development of the FIREWORKS prototype can provide sufficient insight for the evaluation of the economic viability of the relay based network concept.

The FIREWORKS project has been initiated in January 2006 and is currently reaching its completion. The purpose of this paper is to provide some of the major results and achievements obtained from the investigation carried out throughout the project. The following section briefly presents the scenarios and requirements of the FIREWORKS system. Then, several results from a conceptual study of relay-based systems and the design of RRM algorithms are analysed. Section 4 and 5 focus on relay protocols and algorithms for the MAC and PHY layers respectively. The last section contains the current prototyping effort conducted in order to validate the theoretical studies presented within FIREWORKS.

2. Scenarios and Requirements

A brand characteristic of the FIREWORKS concept is that it aims to provide ubiquitous wireless access by investigating techniques for both WMAN (IEEE 802.16) and WLAN (IEEE 802.11) systems. Hence, the wireless nodes are classified into four main types according to their role in the FIREWORKS network architecture, namely Multihop Base Station (MBS), Multihop Relay Station (MRS), Multihop Subscriber Station (MSS) and, Enhanced Mesh AP. The characteristics of these nodes are described in [2].

For the evaluation of the FIREWORKS system and the development of suitable simulation platforms and the demonstrator of the project, five target scenarios and two prototype scenarios have been defined. The five operational target scenarios are parts of FIREWORKS deployment described in Figure 1. Each scenario addresses a different combination of topology characteristics, user profiles and environment. The five scenarios are the Rural (RU), Public transport (PU), Car (CA), City Centre (CI) and the Office (OF) scenario described in [2].

Each of the above scenarios is characterised in terms of distances, channel, power supply, interferences, density and traffic. The service classes supported in FIREWORKS and the related traffic models are defined in [2]. Two of the above scenarios are selected for prototyping.

From the scenarios and the characteristics of the FIREWORKS system, a methodology has been described in [3] for the definition of the system requirements. Three sets of requirements have been defined: system capability (performance, cost, QoS…), system architecture (functional requirements, node characteristics…) and operational characteristics (system management at installation and maintenance, regulatory). Each of the requirements is marked as absolutely essential, essential or non-essential defining in such way levels of importance for their implementation into the final version of the FIREWORKS system.

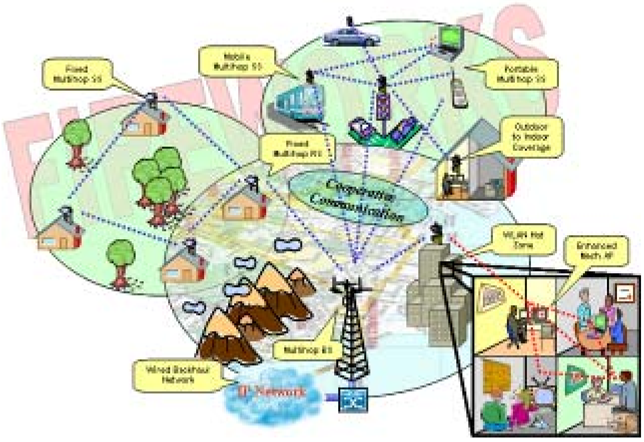

Figure 1. FIREWORKS Deployment

Currently, a business model that includes the various costs associated with the deployment, operation and maintenance of the FIREWORKS system is an ongoing activity of the project. Initial results show that the Relay Station to Base Station ratio must be lower than 1/3 for a cost-efficient deployment. These initial economical estimates are currently refined to incorporate the final specifications of the system and the various simulation results.

3. Relay-based Wireless Broadband Systems

Within FIREWORKS, the traditional cellular point-to-multipoint deployment methodology is extended by relay-based multi-hop communication. Positioning relays within the coverage area of the MBS increases the system's capacity providing coverage to poor propagation conditions such as shadowed areas and outdoor-to-indoor connections. Placing the relays on the cell border serves to extend the cell coverage. Theses scenarios are described in the FIREWORKS deployment shown in Figure 1. To identify the more suitable conditions for the deployment of relay-based systems an appropriate study had to be conducted. Additionally, the novel relay-based deployment must be handled through optimized RRM algorithms capable to support advanced PHY techniques and MAC protocols. Besides these two topics coexistence mechanism for hybrid LAN and MAN multi-hop deployments has been also investigated with FIREWORKS project.

3.1 – Cellular Deployment Concepts

In order to evaluate the enhancements provided by relay-based cell deployment, the capacity increase and performance gain are compared to a conventional single hop deployment. Different performance criteria are considered such as the level of capacity increase or the coverage area range of a relay enhanced BS.

In deliverable 2D1 [4] of FIREWORKS, several studies have been conducted yielding in results that can be use to dimension relay-based cell deployments [5], [6]. In particular, the capacity increase due to the exploitation of Space Division Multiple Access (SDMA) techniques in cellular WiMAX networks has been evaluated [7], [8]. It results that SDMA improves MBS and MRS capacity in cellular conditions especially when both intra and inter cell interferences are well estimated. In particular a system with non-cooperative multi-hop deployment suffers from severe intra-cell interference and hence we have established that capacity enhancement occurs mainly in Manhattan scenarios and in particular when SDM and advanced antenna techniques are used. Coverage extension is also possible. MBS-MRS link capacity is recommended for cooperative relaying conditions in order to achieve important throughput gain. Complex cooperative protocols turned out to provide the best performance. From the study comparing frequency and time forwarding approaches, we concluded that larger capacity is noticed for FDD-based protocols. An expected drawback of relay-based networks is the increased handover signalling from subscriber station mobility.

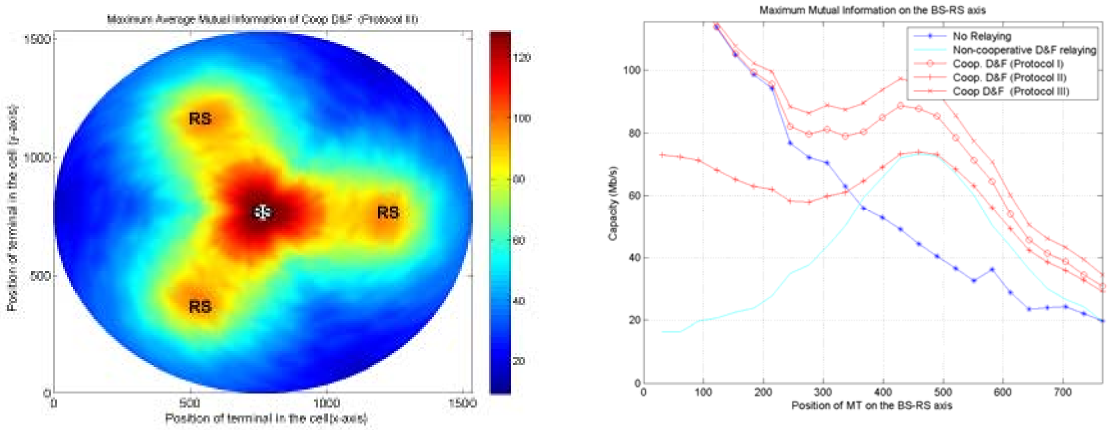

Figure 2. Deployment Capacity of fixed cooperative relays

Figure 2 provides the maximum theoretical throughput of a downlink connection using cooperative Decode and Forward (D&F) technique. The left figure shows the throughput performances in function of the MSS location for protocol III cooperative transmission. The right figure serves to compare the maximum capacities of cooperative versus direct link and simple relaying schemes.

3.2 – Radio Resource Management Algorithms

In order to fully exploit the capacity enhancements offered by flexible relays and advanced antenna techniques, the FIREWORKS system must use enhanced RRM algorithms. The diverse usage of the MRS and the novel deployment concepts lead to the design of individual RRM specific to the desired development.

The provision of end-to-end Quality of Service (QoS) is an important aspect of the network that results from connection admission control, infrastructure design, radio resource assignment and channel-state-aware scheduling algorithms. For mobile terminals, handover algorithms are designed within FIREWORKS to maintain quality control in multihop deployments.

In FIREWORKS, the investigation of advanced RRM techniques is mainly concentrated in the channelization modes of IEEE 802.16e standard [9] in order to derive through evaluation of the performance of these modes several requirements for possible MAC layer modifications. Typical RRM strategies of the standard are extended to the mutlihop forwarding and cooperative cases. Performances of the Adaptive Antenna (AA) and Adaptive Modulation and Coding (AMC) modes for multihop relaying schemes and PUSC-FUSC mode for the cooperative schemes are deduced. The results and conclusions produced for theses modes are issued from studies in mixed-user traffic scenarios. The feasibility of multihop cooperative transmission schemes has been demonstrated with novel techniques that prove their superiority compared to direct transmission.

3.3 – Hybrid MAN and LAN multi-hop Networks

In hybrid LAN and MAN deployments, such as proposed in FIREWORKS as City Centre and Office scenarios, 802.11 Access Points (AP) are connected to 802.16 multi-hop relay-based networks. The WLAN AP of Hot Zones can provide high capacity to the area served by deploying relaying technology to benefit form the advantages of multi-hop systems such as low cost, scalability, extension range and higher capacity.

Both 802.11 and 802.16 networks exhibit different benefits and have different requirements. The switching point between the two relay-based systems is investigated and conclusions are drawn [10], [11], [12]. The coexistence of WLAN and WMAN systems on the same licence-exempt spectrum requires the adaptation of the IEEE 802.16 MAC frame. We consider the case where a Base Station Hybrid Coordinator is capable to operate in both 802.16 and 802.11 protocol mode. The realization of the interworking between the two standards has been studied within FIREWORKS and shows some promising performance in term of channel occupancy and total system throughput.

4. Advanced Relay-based MAC

The control and management of the enhancements required in multi-hop relay-based networks leads to the design and specification of an advanced MAC protocol capable to incorporate the relaying functionality and adaptive antenna techniques such as cooperative communication, SDMA, transmit diversity and spatial multiplexing.

4.1 – MAC Protocol design for Relaying Systems

The usage of flexible relays has an impact on the MAC layer. Key requirements directly derived from the conceptual study and RRM solutions proposed are taken into account in order to design MAC protocols for relay systems. The characteristics of the different adaptive antenna PHY techniques investigated in FIREWORKS are integrated into the design of novel MAC protocols. Initially, the IEEE 802.16e standard [9] is taken as reference and enriched with novel MAC functionalities capable to support the relaying strategies and the PHY techniques of the project.

Initially, the MAC Common Part Sub-Layer is investigated. The MAC management procedures to support multi-hop RRM algorithms and the mechanisms for the sharing of information concerning the link quality of the nodes throughout the network are depicted by respective message sequence charts. Then, the basic issues and principles involved in supporting advanced PHY techniques by the MAC layer protocol are identified and described [13], [14]. The implementation of cooperative techniques within the 802.16e standard is described in [15].

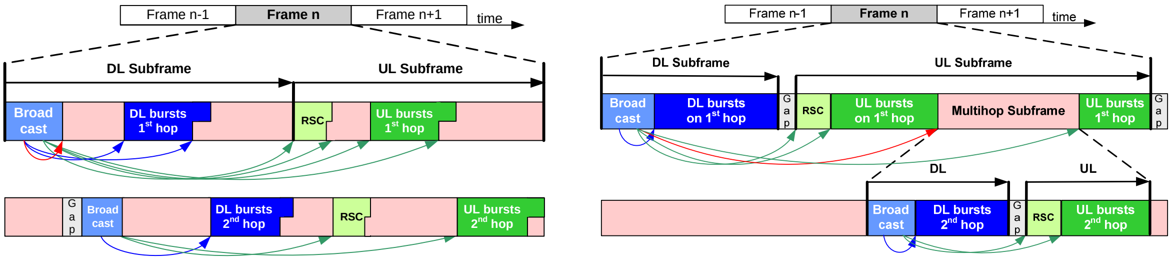

Figure 3. Multi-hop MAC frames

In order to support multi-hopping and cooperation, novel MAC frame structures that try to follow the requirements of the IEEE 802.16j task group [16] are presented. The MAC frames are capable to accommodate different cooperative protocols providing additional flexibility to the user and can differ for downlink and uplink transmissions.

Figure 3 shows two of the MAC frames investigated within FIREWORKS for Time Domain OFDMA Relaying. The left figure concerns a system with centrally control relay stations while the right figures shows the MAC frame when relays are de-centralized. The top and bottom frame structures correspond to the base and relay stations respectively.

Finally, the possible modifications of the primitives of the MAC and PHY access points due to the introduction of relays are investigated. Two approaches regarding the timing and appliance of these primitives are suggested. A complexity estimation of the MAC enhancements needed to support the features of FIREWORKS system is produced [7], [8].

4.2 – MAC Protocol specifications and performances

Based on the results from the MAC protocol design activity, specifications enabling the support of simple relay and cooperative relay are extracted assuming the usage of advanced antenna techniques and IEEE 802.16 concept as basis. The MAC specifications span from the definition of the MAC common part sublayer to the support of relaying and cooperative techniques. Handover, entry procedures, node association and disassociation, service flow management, frame structures, relaying and cooperative support are some of the MAC issues specified within FIREWORKS. MAC messages are created or extended. Frame structures and MAP messages are modified. Novel MAC procedures are identified and described.

From the work carried out for the definition of novel PHY techniques, the characteristics of the MAC/PHY interface are identified. The support of advanced antenna techniques requires the detailed definition of both control and data paths at each node especially in order to support relaying and cooperative schemes. In FIREWORKS, a substantial set of API primitives are defined and are capable to support and extend the functionalities of an IEEE 802.16e system.

Finally, the almost completed performance evaluation of the MAC protocols designed and specified within FIREWORKS provides comparable results of non-relaying and relaying scenarios from which interesting conclusion can be drawn. The simulation environment models wireless channels and generate realistic traffic load based on the FIREWORKS scenarios [17].

5. Advanced PHY Techniques

The development and investigation of novel Multi-Transmit Multi Receive (MTMR) under the prism of relaying and cooperative multi-hop environment is essential in FIREWORKS. A specific set of MTMR techniques are considered for the FIREWORKS system. These techniques form an Advanced Antenna System (AAS) and are investigated according to the cases where relaying and cooperation occurs at Layer 2 and above, or when Layer 1 (L1) relaying and cooperative transmission-reception is possible.

A major prerequisite for the proper evaluation of the techniques is the utilization of appropriate channel models characterizing the radio environment of relay-based systems. Propagation scenarios modified for the FIREWORKS scenario conditions are provided.

For the basic single-hop conditions, Space Time Block Coding (STBC), spatial multiplexing, and uplink and downlink beam-forming techniques are considered in [18]. The Golden code, a downlink SDMA technique using Obèle algorithm and, several typical and efficient multi user detection techniques for the uplink SDMA such as Maximum Likelihood (ML), Least Square (LS), Minimum Mean Square Error (MMSE) linear detectors, Serial Interference Cancellation (SIC), SIC with State Insertion (SIC-SI), and Soft-Input Soft-Output (SISO) sphere detectors are considered.

When relaying and cooperation are explicitly carried out in L1, cooperative transmission techniques with one or more relay nodes and at most two-hop communication are considered. Different Amplify and Forward (AF), Decode and Forward (DF), Compress and Forward (CF) and a low complexity Quantize and Forward (QF) technique are investigated in [18]. Performance results confirmed that DF techniques require reliable link between sources and relay nodes, especially when distributed turbo code is deployed. In contrast to DF, CF techniques require relay to destination reliable links. Finally, relay selection with Hybrid Automatic Request (HARQ) in conjunction with distributed turbo code for DF cooperation provide reliable and robust performance for wide range of links' SNRs.

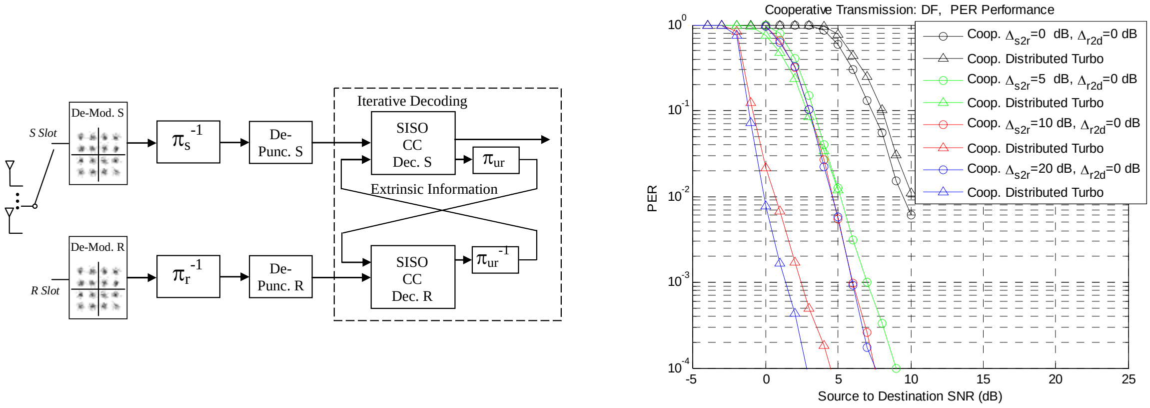

Figure 4. Comparison of DTC and CC for a cooperative DF scheme for high mobility

In [18], performance results for Distributed Turbo Codes (DTC) [19] are compared with typical Concolutional Codes (CC) for different conditions when single-antenna single-relay cooperative DF protocol is employed in a high mobility scenario. While CC is able to deliver better performance at low Source-Relay (S-R) SNR offsets, DTC starts to take over at moderate S-R SNR offsets.

The exploitation of the traditional MTMR PHY techniques for the FIREWORKS relay-enhanced communication system where relaying is not explicitly visible in its PHY layer is described in [20]. Beside the typical MTMR techniques investigated under this framework, a Dynamic Band Allocation (DBA) methodology is also discussed based on WiMAX subcarrier mapping options. It is shown that the existence of the relay nodes can still be efficiently exploited to enhance the system performance. Selection and application of different MTMR techniques to different scenarios produces a scenario/techniques mapping that recommends the type or types of MTMR techniques to be used for each scenario in selected and tuned channel models. This mapping leads to the definition of an AAS.

Finally, novel and innovative coding and modulation techniques for cooperative communications based on either AF, DF, and CF are presented an analysed in [21] (see also [22]-[26]).

6. Prototyping and Validation

One of the ongoing major outcomes of the project is to prove the technical feasibility of the relay-based concept following the FIREWORKS framework. To this end, a testbed based on prototype versions of the nodes must be established. The prototype targets to demonstrate selected MTMR techniques and MAC protocols studied during the project (sections 4 and 5). A Real-Time Advanced Antenna Radio Emulation (RTAARE) environment, supporting also MIMO links, has been developed to replace the air interface between the three nodes. In a first step, the RTAARE allowed to perfectly control the propagation channel between nodes. From the different operational scenarios identified, only the short-term promising rural and city centre scenarios have been selected for implementation. For both, we consider the simple relaying and cooperative cases.

The RTAARE is a central entity of the prototype responsible for the emulation of the air interface between the 3 nodes for the simple relaying and cooperative relaying scenarios.

The FIREWORKS prototype is composed of three of the basic nodes, i.e. a MBS, a MRS and a MSS. The demonstrator mainly follows IEEE 802.16e specifications. The appropriate PHY and MAC blocks are modified to support relaying and cooperative schemes. Each node of the prototype is a powerful network processor / DSP board composed of two massively parallel DSP processors, the picoChip PC102 [27] that performs all the PHY signal processing and an integrated processor, providing the control and management of the system. The WinPath1 network processor from Wintegra [28] for the BS and the Freescale MPC8560 processor for the SS are used. The MRS node is composed of two boards – one typical BS and one SS board – in order to simply the implementation of advanced features at the MRS. A back-to-back Ethernet connection is created between the two boards of the relay network entity that bridge the transceivers of the two boards. Finally, a passive adaptor board has been created to interconnect the nodes and the FPGA board used for the RTAARE.

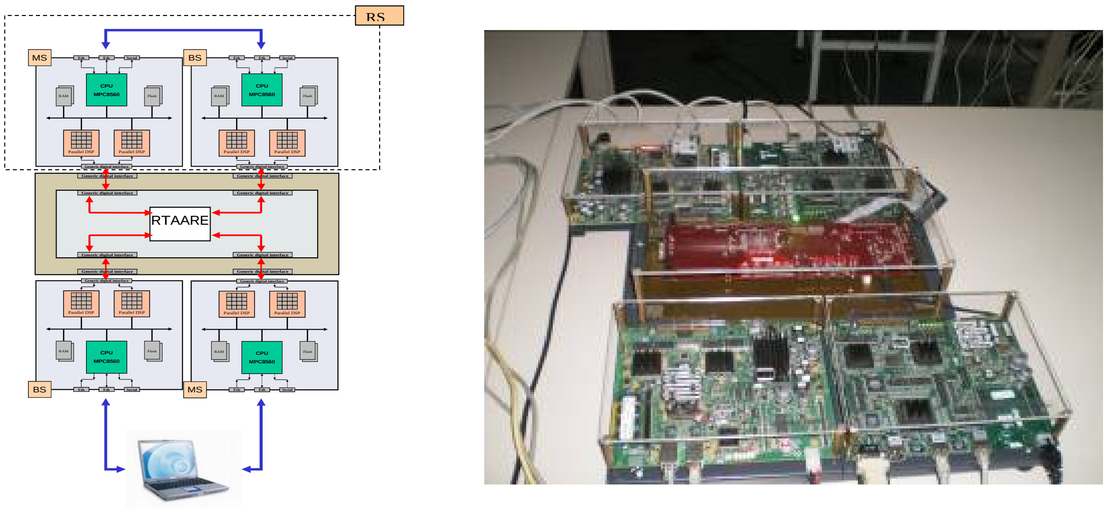

Figure 5. The FIREWORKS prototype

A Graphical User Interface (GUI) serving to control the nodes of the prototype and gather performance metrics of interest is currently under development.

Within the prototyping activity of FIREWORKS, an analysis of the RF front end and antennas for relays through simulations has been investigated in order to propose a guideline for the antenna and specifications for the RF front end.

7. Conclusion

Several approaches, concepts, techniques and protocols have been investigated within FIREWORKS forming a reliable framework for optimal exploitation of relays in WMAN. The identification of optimal requirements for relay-based deployment, the design of advanced RRM algorithms, the investigation of hybrid WMAN/WLAN solutions and the development of novel MAC and PHY techniques define the FIREWORKS system making it capable to provide ubiquitous radio coverage under challenging environmental conditions, achieve high QoS requirements and flexibly adapt to changing users' behaviour or environmental conditions. The FIREWORKS project has completed the definition of specifications for a next generation BWA system based on relays.

The results obtained within FIREWORKS are going to be extended in the FP7 project ROCKET (Reconfigurable OFDMA-based Cooperative NetworKs Enabled by Agile SpcTrum Use) [29] with research on opportunistic spectrum usage, advanced multi-user cooperative techniques, inter-cell coordination and reconfigurable MAC procedures.

References

[1] FIREWORKS IST-027675 STP, project details are available at http://www.ist-fireworks.eu/

[2] FIREWORKS consortium, “Service requirements and operational scenarios”, IST project FP6-027675, Deliverable 1D1, May 2006.

[3] FIREWORKS consortium, “Report on System Requirements”, IST project FP6-027675, Deliverable 1D2, September 2006.

[4] FIREWORKS consortium, “Cellular deployment concepts for relay-based systems”, IST project FP6-027675, Deliverable 2D1, September 2006.

[5] Hoymann, C. et al.”Dimensioning Cellular WiMAX Part II: Multihop Networks” European Wireless, Apr. 2007, Paris, France.

[6] Hoymann, et al. “Dimensioning Cellular WiMAX Part I: Singlehop Networks” European Wireless, Apr. 2007, Paris, France.

[7] Hoymann, C. et al. “MAC Frame Concepts to Support Multihop Communication in IEEE 802.16” Proceedings of the 16th Wireless World Research Forum, Apr. 2006, Shanghai, China.

[8] Klagges, K. et al. “Performance Analysis of the Subframe Concept in the IEEE 802.16 Network, European Wireless Conference, Apr 2007, Paris, France.

[9] IEEE Std. 802.16e-2005: Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems-Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands. 2006. ISBN 0-7381-4857-1.

[10] Berlemann, L. et al. “Coexistence of IEEE 802.16 and 802.11(a) in Unlicensed Frequency Bands” Wireless World Research Forum WWRF16, Apr. 2006, Shanghai, China.

[11] Berlemann, L. et al. “Unlicensed Operation of IEEE 802.16: Coexistence with 802.11(a) in Shared Frequency Bands” Proceedings of the 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Sep. 2006, Helsinki, Finland

[12] Berlemann, et al. “Coexistence and Interworking of IEEE 802.16 and IEEE 802.11(e)” VTC2006-Spring, May. 2006, Melbourne, Australia.

[13] Hoymann, C. et al. “Evaluation of Grouping Strategies for an Hierarchical SDMA/TDMA Scheduling Process” Proceedings of the IEEE International Conference on Communications, Jun. 2007, Glasgow, UK.

[14] Pabst, R. et al. “System Level Performance of Cellular WiMAX IEEE 802.16 with SDMA-enhanced Medium Access” Proceedings of IEEE Wireless Communications & Networking Conference, Mar. 2007, Hong Kong, China.

[15] FIREWORKS consortium, “Design and specification of MAC in relay-based cooperative networks”, IST project FP6-027675, Deliverable 3D1, July 2007.

[16] IEEE 802.16’s Relay Task Group, details available at http://www.ieee802.org/16/relay/

[17] FIREWORKS consortium, “Performance evaluation and final specification of the enhanced MAC protocol”, IST project FP6-027675, Deliverable 3D2, February 2008.

[18] FIREWORKS consortium, “Preliminary description of the PHY techniques for Relay/Mesh based Networks”, IST project FP6-027675, Deliverable 4D1, November 2006.

[19] Y. Li, B. Vucetic, T. F. Wong, M. Dohler, “Distributed Turbo Coding With Soft Information Relaying in Multihop Relay Networks,” *IEEE* Journal on Select. Areas in Commun. (JSAC) Vol. 24, No. 11, pp. 2040-2050, Nov 2006.

[20] FIREWORKS consortium, “Detailed description of AAS and selected PHY techniques for Relay/Mesh based Networks”, IST project FP6-027675, Deliverable 4D2, September 2007.

[21] FIREWORKS consortium, “Detailed description of Coding and Modulation Techniques for L1 Relaying and Cooperative Communication”, IST project FP6-027675, Deliverable 4D3, December 2007.

[22] S. Simoens, O. Muñoz, J. Vidal, A. D. Coso, *“Compress-and-Forward Cooperative Relaying with full MIMO Channel State Information”*, IEEE International Conference on Communications (ICC 2008), 19-23 May 2008, Beijing, China.

[23] S. Simoens, O. Muñoz and J. Vidal, *“Achievable Rates of Compress-and-Forward Cooperative Relaying on Gaussian Vector Channels”* at IEEE ICC 2007 conference, Glasgow, June 2007.

[24] R. Hoshyar, and R. Tafazolli, *“Soft Decode and Forward of MQAM Modulations for Cooperative Relay Channels”* to appear in VTC Spring, May 2008, Marina Bay, Singapore

[25] Y. Qi, R. Hoshyar, and R. Tafazolli**,** *“Soft Multilevel Slepian-Wolf Decoding in Systems Using Turbo Joint Decoding and Decompressing”* , at VTC Spring, May 2008, Marina Bay Singapore

[26] E. C. Strinati, S. Yang and J. C. Belfiore**,** *“Adaptive Modulation and Coding for Hybrid Cooperation Networks”*, IEEE International Conference on Communications, 24-28 June 2007, Glasgow.

[27] PicoChip, “PC102 Product Brief”, available at http://www.picochip.com/

[28] Wintegra, “WinPath1 Family Product Brief”, available at http://www.wintegra.com/

[29] ROCKET ICT-215282 STP, project details are available at http://www.ict-rocket.eu/