The FP7 ROCKET Project: Wireless Access Technology for Homogeneous High Rate Coverage

Sébastien SIMOENS[1], Ilias PANAGIOTOPOULOS[2], Shyamalie THILAKAWARDANA[3], Patrick LABBE[1], Josep VIDAL[4], Benedikt WOLZ[5], Klaus SAMBALE[5], Lionel RUDANT[6], Reza HOSHYAR[3], Diego SORO[7], Enrico DE MARINIS[8], Adrian AGUSTIN[4], Zdeneck BECVAR[9]

[1]MOTOROLA Labs, Parc Les Algorithmes Saint-Aubin, 91193Gif-sur-Yvette CEDEX France simoens@motorola.com, patrick.labbe@motorola.com
[2]INTRACOM S.A Telecom Solutions, Wireless Systems and Technologies Dept.,19.5 km Markopoulo Ave, 19002 Peania Attika, Greece ipan@intracom.com
[3]University of Surrey, Centre for Communication Systems Research, School of Electronics and Physical Sciences, Guildford, GU2 7XH, UK s.thilakawardana@surrey.ac.uk
[4]Universitat Politècnica de Catalunya, Dep. Teoria del Senyal i Comunicacions, Campus Nord UPC, Jordi Girona 1-3, E-08034 Barcelona, Spain josep.vidal@upc.edu, agustin@gps.tsc.upc.edu
[5]Lehrstuhl für Kommunikationsnetze der RWTH Aachen, Templergraben 55, D-52056 Aachen bmw@comnets.rwth-aachen.de, ksw@comnets.rwth-aachen.de
[6]CEA / DRT / DCIS, 17, rue des Martyrs, 38054 GRENOBLE Cedex 9, France lionel.rudant@cea.fr
[7]Iber Wifi Exchange SL, Paseo de la Castellana 21, 28046 Madrid, Spain dsoro@gowex.com
[8]DUNE SRL, Via Tracia, 4, 00183 Roma, Italy demarinis@dune-sistemi.com
[9]Faculty of Electrical Engineering, Department of Telecommunications Engineering, Technicka 2, 16627 Praha 6, Czech Republic becvaz1@fel.cvut.cz

Abstract: The FP7 ROCKET project aims at designing Broadband Wireless Access (BWA) technology that enables a larger number of users to be served at a high data rate in both urban and rural deployment scenarios. The technical approach relies on the combination of 1)advanced coordination and cooperation of Base Stations (BS) and Relay Stations (RS) in order to increase the area spectral efficiency 2)operation on larger bandwidth, including an opportunistic/flexible spectrum usage that adapts to the different capabilities of the network devices (BS,RS,MS) 3)optimized signaling that minimizes the MAC overhead for basic functionalities such as scheduling and handover and the backhaul load required to support the advanced spectrum usage, mobility (i.e. handover) and cooperation mechanisms defined in the project. Finally, the antenna integration constraints and the implementability of selected key algorithms will be studied thanks to a state-of-the-art hardware and software prototyping platform.

Keywords:. 4G, cooperative, cognitive, relaying, coordination, efficiency, IMT-advanced

Introduction:

Although the IMT-advanced peak bit rate requirements of 1Gb/s for nomadic and 100Mb/s for mobile users **Fehler! Verweisquelle konnte nicht gefunden werden.** represent a significant step forward compared to the capabilities of IMT-2000 systems, future Broadband Wireless Access (BWA) systems will likely have to address several additional requirements in the coming years which translate into different constraints on the technology. In cities and suburbs, where DSL, cable and Fiber have a high penetration rate [2], customers can benefit from triple or quad-play services at bit rates often greater than 8Mb/s and at a price typically lower than that of a 3G/3G+ unlimited data subscription. BWA is already provided by IEEE 802.11 WLAN technology but the outdoor coverage in cities is often limited to a number of hotspots. The ongoing deployment of IEEE802.16e WMAN in several European (e.g.[3]) and U.S.[4] cities is expected to improve the coverage and offer (when regulation permits it) handover capability. For at least some of these deployments (e.g.[4]) it is stated by the operators that the target service is DSL-like access with a small price premium for mobility. However, a simple calculation shows that the traffic generated by fixed broadband access users per squared kilometer in cities is in the order of several Gb/s/km^2, that is several orders of magnitude larger than the area spectral efficiency promised by either Mobile WiMax [4] or 3GPP-LTE. Reducing this gap will likely require to simultaneously increase the area spectral efficiency, while also increasing the total bandwidth available to the system [13]. In rural areas, the challenge of BWA is to provide a cost-efficient coverage of large areas while still providing user bit rates similar to those experienced in cities. This goal seems to call for an increase of the cell range, while keeping a high cell spectral efficiency. In terms of regulation, several hundreds of MHz of spectrum are now identified or allocated to IMT-2000 and IMT-advanced systems [11][12]. However, this spectrum is not contiguous and its practical availability changes on a regional or even national basis. Interestingly, this spectrum includes some bands (e.g. the 790-862 MHz band) which are well suited to large range propagation and building penetration, while some others (e.g. the 3.4-3.6 GHz) are better suited to short-range/dense deployments or directional wireless backhaul links.

The ROCKET FP7 project [5] -which started in January 2008- aims at designing BWA technology that addresses these challenges for both rural and urban deployments. A first core technology investigated in ROCKET is cooperative relaying. In urban environments, fixed Relay Stations (RS) can be deployed within each cell sector, preferably close to cell edge. In FP6 FIREWORKS project, it is shown [7] that the cell capacity is significantly increased when the RSs are spatially multiplexed by the BS and when the time-frequency resource allocated to the transmissions between RSs and Mobile Stations (MS) in Uplink (UL) and Downlink (DL) can be reused within the cell. In rural deployments, non-transparent relaying can be used to extend the coverage beyond the range of the BS, with the RSs broadcasting the beacon for these remote users. In both cases, a mixed deployment of BSs and RSs is expected to reduce the CAPEX+OPEX at equivalent coverage/capacity, compared to a conventional BS deployment, thanks to less expensive device, site acquisition and backhaul. ROCKET will leverage the achievements of FIREWORKS and will investigate advanced concepts such as two-way relaying and multi-user/multi-relay cooperation, which are expected to further increase the system spectral efficiency.

In general, because the user distribution is typically uniform, the weight of users on the aggregate cell capacity under fair scheduling increases linearly with the distance from the BS. Therefore, one goal of ROCKET is the homogeneous provision of high rate over the cell. Cooperative relaying is one of the means to achieve this goal, but another alternative is Base Stations coordination and cooperation. For instance in a synchronized network, neighbouring BSs can coordinate their time-frequency resource allocation in the upcoming MAC frames, in order to reduce inter-cell interference. Base Stations can even exchange data bits or quantized signal samples on the backhaul [8][9], in order to form a Distributed Antenna System (DAS). Creating a DAS naturally leads to large spectral efficiency gains as inter-cell interference is turned into a constructive signal, but it also rises several new issues related to BSs and MSs grouping [10], load and latency characteristics of the backhaul and their interaction with the signal processing aspects of the DAS. In ROCKET, cooperative relays and BSs will be addressed both separately and also as two complementary components of a deployment.

As a result of the predicted spectrum allocations for IMT-advanced, ROCKET will also investigate techniques to

- operate on large channels (typically from 20 MHz to 100MHz) and exploit these large channels to improve the aggregate cell throughput
- operate on multiple-bands, possibly simultaneously, and leverage the characteristics of these bands (e.g. propagation, interference)
- coexist or even cooperate with other primary and secondary systems in one or several of the above-mentioned frequency bands
- maintain a high MAC efficiency while allowing flexible spectrum usage, high physical bit rates and large number of scheduled users per MAC frame

The ROCKET project plans to leverage and contribute to the IEEE802.16m Task Group. which addresses the IMT-advanced requirements, with a target completion by the beginning of 2010. Future evolutions beyond 3GPP-LTE will also be monitored.

These aspects are addressed in section 1 of this paper, while the ROCKET perspective on cooperation of Base Stations and Relays is detailed in section 2.

1 Increasing the bandwidth, and exploiting it efficiently

Within ROCKET, concepts of flexible spectrum usage are studied enabling the target system to provide ubiquitous high rate coverage by not only operating with an increased assignment of spectrum but also implementing dynamic spectrum access techniques.

1.1 Increasing the amount of spectrum allocated

Large bandwidth channelization can be used to provide very high bit rates not only to users close to a BS but also to all the cell. Indeed, large channels are especially useful to interconnect a fixed RS with the BS or with another fixed RS when link budget is strong enough (e.g. LOS). The fixed RS will then be able to distribute/aggregate higher throughput to/from the surrounding MSs. The large available frequency resource can also be exploited to improve the BS-RS, RS-RS or even BS-BS cooperation to increase the throughput of a given user, by e.g. forming a large virtual receive antenna array in uplink using Compress-and-Forward relaying (see e.g. [14][20]). Similar resource allocation trade-offs exists in the downlink. Within ROCKET resource allocation trade-offs will be investigated by system-level simulations under various fairness constraints in order to assess the gain of wideband channelization on the whole system.

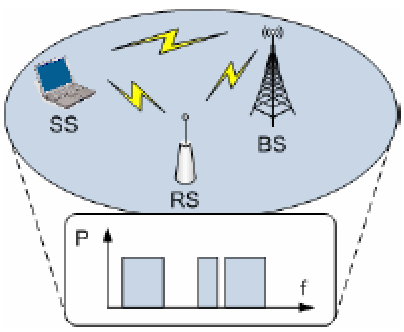


Figure 1: Scattered multi-band operation in a single BS-RS-SS Communication

Also scattered multi-band operation (Figure 1) is a promising way to increase the target system performance. Simultaneous multi-band operable devices will allow the radio system to flexibly operate in multiple frequency bands over a wider range of radio spectrum. This will increase the overall system bandwidth and thereby the overall throughput. MAC functionalities supporting this functionality will be specified as well as allocation mechanisms that take into account the characteristics of the different bands (interference, propagation). For example under NLOS conditions or while serving MSs, lower frequencies (e.g. <1GHz) are preferred whereas under LOS conditions typically higher frequencies (e.g. >5GHz) can be preferred especially if the device is equipped with directional antennas (BS or RS). Thus, multi-band capability will also be investigated at the system-level to account for its interactions with e.g. cooperative relaying.

1.2 Mechanisms for flexible spectrum usage

Exclusive assignment of spectrum to a system might not always provide the required amount of spectrum. Dynamic and flexible access to radio spectrum can then be employed in order to make additional resource available. Agile or Cognitive Radios (CR) allow for local identification and exploitation of unused spectrum while assuring that primary systems are not interfered. CR systems identify empty spectrum opportunistically and intelligently on the basis of observation. In this project, key MAC functionality for efficient support of dynamic access to radio spectrum is identified such as certain signalling procedures or re-configurability capabilities. The system is empowered by enabling its different types of stations (MS, RS, BS) to change the radio spectrum they are operating on. When bands are dynamically changed, this can be done on the basis of entire continuous spectrum band or only on the basis of sub-bands.

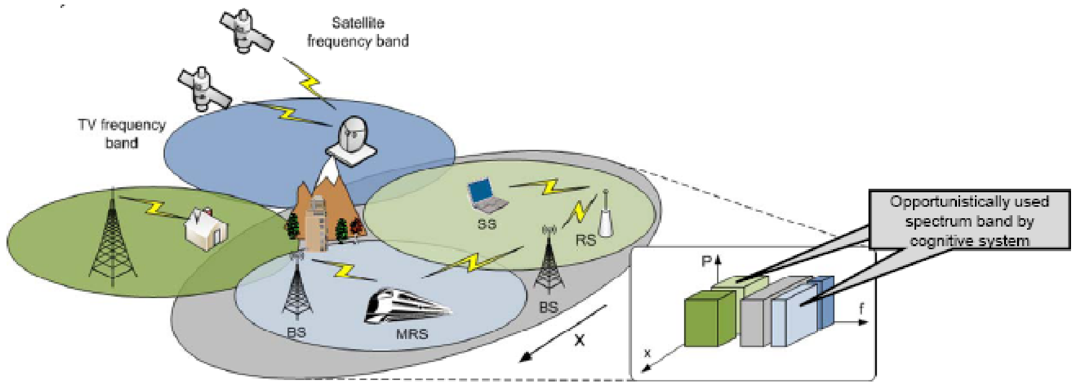


Figure 2: Dynamic band allocation through opportunistic spectrum usage from secondary spectrum from multiple systems

Availability of the spectrum bands may depend on time/location: competing CR systems or re-occurring primary system cause time dependency, moreover receiving-only stations and systems with minimum receive power may require local zones with exclusive spectrum access. Several coexistence scenarios are covered by the above mentioned opportunistic spectrum usage scenarios (i.e. re-use of entirely empty bands) such as radar or satellite systems (Figure 2). When designing the MAC functionalities required for coexistence, focus is on system coexistence of the same standard which is required in scenarios of involving one or multiple operators. These concepts rely on the predictability of observation-based spectrum access. One application might be the simultaneous low power coexistence. Another technique leverages pre-existing knowledge of the primary system

1.3 Impact on the MAC design

The MAC protocol needs to be significantly imporoved to reach higher spectral efficiency and support larger bandwidth operation. First the spectral efficiency can be increased by reducing the MAC overhead ratio. Second when different bandwidths and center frequencies are employed, gains can be expected by adapting the MAC protocol to the changing transmission environment. To provide seamless high rate connectivity and low delays to high mobile users handover algorithms have to be enhanced. A promising approach to reach this goal is the additional assessment of mobility dependent user parameters in handover decisions.

Design of an ultra-efficient MAC protocol

Overhead ratio of current MAC protocols such as WiMAX lies around 10% depending on the scenario and traffic types. Although future high rate service causes by nature a lower overhead ratio, low data rate traffic types such as VoIP will also be provided and demand for signaling reduction. When the bandwidth per MAC entity is heavily increased, keeping a low signaling overhead is a challenge. The overhead can be reduced for instance while indicating frame based transmissions. Three promising approaches for reducing map overhead will be applied in ROCKET (1) employing high capacity PHY transmission schemes (higher order modulation, virtual MIMO, etc.) for maps considering that remote stations have still to be served, (2) using differential maps which leverage periodicity of traffic and only indicate changes of the resource allocation and (3) the frame descriptor table concept optimized for relay deployments which was developed in WINNER [16] project. Seamless provision of high data rate demands also enhanced handover strategies with reduced handover durations which will further increase the overall spectral efficiency and user satisfaction. Handover procedures can be improved for example (1) by optimizing the communication among the MS and involved BSs/RSs, (2) by handover decisions considering uplink and downlink signal quality[19], or (3) by evaluating the trajectory of users or generating cell coverage maps .

Design of a reconfigurable air interface

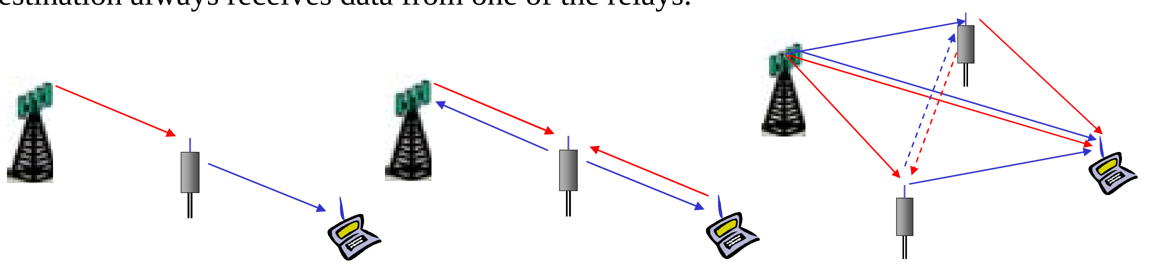
According to the plan of using a single MAC protocol for an enhanced PHY layer that operates over a wide frequency range, the used protocols have to adapt themselves to the transmission environment. Distinct MAC and PHY parameters (such as packet length, choice of ARQ type or FEC, ARQ window size) are adapted to transmission characteristics during runtime such as increased channel bandwidth or QoS requirements (e.g. traffic dependent delay constraints or PER). ROCKET targets at identifying MAC and PHY key parameters enabling performance gains through reconfiguration and analyzing their mutual dependencies in a systematic manner. Eventually guidelines will be derived for the reconfiguration for different system conditions. Following three examples of reconfiguration will be part of the considered parameter space to be configured during runtime.(1) The adaptation of the transmission interval of channel state information is a reconfiguration of the MAC/PHY protocol: the higher the carrier frequency is, the stronger is the Doppler spread. Hence, channel state information has to be transmitted more often with increasing carrier frequency for mobile users. (2) The MAC can also beneficially be adapted by increasing ARQ retransmissions timeout during runtime when less bandwidth becomes available to the system. Reducing the bandwidth results in larger packet delay and hence requires larger roundtrip time but increasing the ARQ retransmission timeout avoids unnecessary ARQ retransmissions. (3) The optimal packet size determined by the SAR configuration depends on the PER[17]. If the PER increases the optimal packet size decreases in order to reach the lowest overhead to payload ratio.

2 Coordination and Cooperation for efficiency and uniform coverage

The definition of *coordination* and *cooperation* concepts in the literature depends on the domain and context. Here we arbitrarily define them based on the nature of information shared by the involved network entities *i.e.* cooperation refers to a sharing of a common control and data plane among all the involved parties, whereas coordination exercises sharing limited only to control plane. Cooperation and coordination concepts can be applied to almost all possible communication scenarios including point-to-point, point-to-multipoint, (Broadcast Channel (BC)), and multipoint-to point (Multiple Access Channel (MAC)), but also in different scales from user and group of users to radio system level (including relays and base stations), where cooperation and coexistence of systems are addressed. Full sharing of radio network resources at different levels and scales even though it allows for optimized theoretical performance may also put huge amount of burden on the access network and radio network components in terms of processing and signalling overhead. In this regard, limited level and scale of sharing through coordination concept should be exercised where the trade between performance gain and processing overhead is beneficial. ROCKET plans to assess different patterns of coordination and cooperation in three main scenarios of increasing complexity depending on the level in the transmission chain where the cooperation occurred: at the user, the relay or the base station level.

2.1 Cooperative Relaying

Although there is already a vast literature on cooperative schemes, some aspects of single-user cooperative relaying are still not well understood and require more investigation, for instance closed-loop techniques exploiting different levels of Channel State Information at the source and relay terminals. Also new protocols that use multiple relays or joint scheduling of UL and DL transmissions promise superior spectral efficiency. Figure 3 illustrates some of the envisaged protocols as the two-way relay channel (TWRC) and the two-path relay channel (TPRC) [21]. The first protocol assumes a bidirectional relay which allows the communication between two users. Additionally, the TPRC combats the half-duplex constraint of the relays by means of alternating the transmission from two relays, i.e. when one is receiving data the other is transmitting to the destination. In this sense, the destination always receives data from one of the relays.



BS	Tx		Tx
RS	Rx	Tx	Rx
MS		Rx	

BS	Tx	Rx	Tx
RS	Rx	Tx	Rx
MS	Tx	Rx	Tx

BS	Tx	Tx	Tx
RS_1	Rx	Tx	Rx
RS_2	Tx	Rx	Tx
MS	Rx	Rx	Rx

Figure 3 : The conventional relay channel (left), the two-way relay channel (center) and the two-path relay channel (right). Red line: phase I of cooperation. Blue line: phase II of cooperation. Dashed line: interference.

Single user relaying can benefit from all the possible matured techniques developed for conventional non-cooperative communications, such as multiple antenna transmission and reception, advanced coding and modulation and also adaptive transmission techniques that try to efficiently exploit the available transmit channel knowledge. Application of hybrid ARQ concepts in conjunction with selective relaying is also promising. However it should be strongly emphasised that direct application of non-cooperative techniques is not optimal and may not truly exploit all the possible degrees of freedom available in a cooperative scenario. While for non-cooperative case the advanced coding and modulation techniques have considerably reduced the gap between achieved performances and the anticipated capacity bounds, still effort should be made in optimisation of the cooperative communication strategies to approach their corresponding capacity bounds. Transmission and reception techniques should be revised to collectively take into account the erroneous conditions of all the involved cooperative links. Also more information theoretic treatment are required to anticipate capacity bounds for cooperative systems with practical limitations such as finite alphabet constellations and limited form of available channel knowledge [14].

Cooperative transmission concept can be extended to cases beyond single source-destination pair communication. It can be incorporated into broadcast and multiple access channels, where a single source attempts to transmit data to multiple of destinations or several sources send data to a single destination. Finally it can be extended to multiple source and destination scenarios. Obviously huge number of possibilities for cooperative transmission can arise depending upon the number of involved source, destination, and relay nodes, their relative positions, their capability and limitations in terms of energy, power, number of antennas per node, processing, and storage (data buffering). Also the availability of the channel and data knowledge, and the type and level of that knowledge will be an effective factor in deciding of appropriate transmission-reception strategy to be taken by the involved nodes. Notice that a relay may know the interfering signal experienced by its associated end user and due to others relays, if it has been able to decode the signal intended to those relays. In such a case, it may exploit Dirty Paper Coding and network coding techniques to avoid the interference.

The effective concepts developed and matured for single user case could be a starting point that can be further extended towards multi user scenarios by integration of some effective multi user techniques. As an example Figure 4 illustrates how a single user two-way cooperative relaying strategy could be extended to a multi user application.

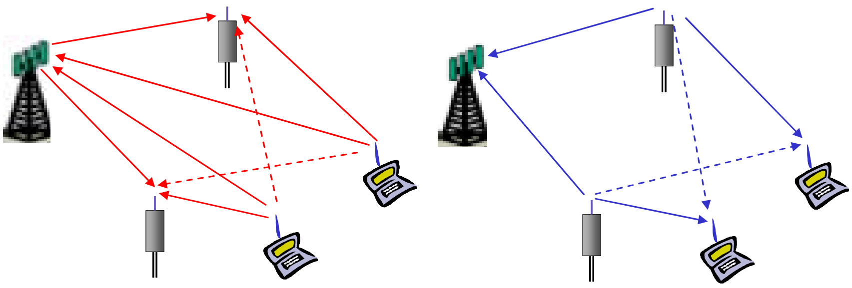


Figure 4 A possible extension of the two-way relay channel to the multi-user case. Phase I (left) and phase II (right). Dashed line: interference.

Similar to non-cooperative case, the objective of a multi-user cooperative communication is to make users' communication cost-efficient whilst satisfying users respective quality of services in terms of delay, throughput, bit and block error rates. The cost of the system depending on the limitations of the wireless system could be consumed bandwidth, and power, and even energy of the radio nodes. The potential of creating virtual multi antenna nodes, and the awarded spatial processing capability, and also possibility of establishing several routs between several sources-destinations should be exploited not only in form of improvement of single-user communication but also in interference avoidance, cancellation, and joint multi-user transmission-reception techniques. This will help to minimize the respective costs and make the overall communications as much efficient as possible.

2.2 Multi-cell interference management and RRM

This scenario assumes that neighbouring BSs (and RSs) are serving only users of their own cell, see for example Figure 5. Therefore, provision of cell edge user with high data rate might cause interference among them, basically due to the transmission from the RSs. Additionally, there will not be a frequency planning as in conventional cellular networks, hence the radio resources can be dynamically allocated as a function of the traffic demand of each cell. Finally, the amount of spectrum obtained through flexible spectrum usage (section 2), adds more complexity to the radio resource management.

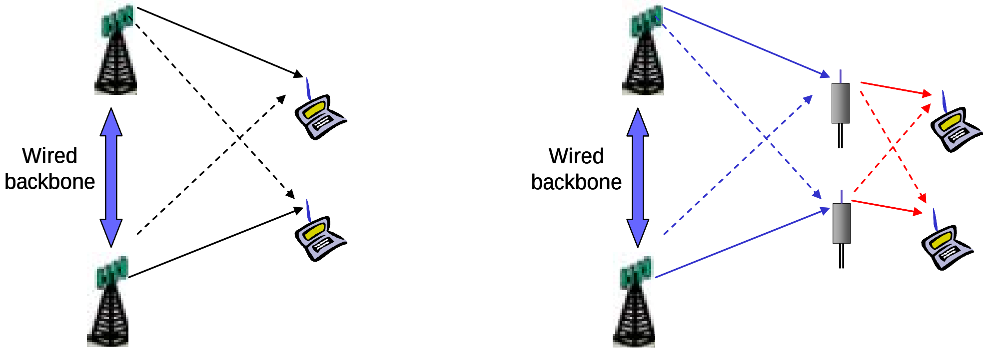


Figure 5 Cooperation between BS through wired backhauls, with and without the intervention of relay terminals (only DL services are plotted for brevity). Blue line: phase I of cooperation. Red line: phase II of cooperation. Dashed line: interference.

The solution envisaged for this scenario is the *coordination* or *cooperation* between BSs for improving the system throughput. The level of coordination will depend on the behaviour of each cell (selfish behaviour or full coordination), the type of control information shared among the BS (there is perfect CSI knowledge when BSs are connected through the wired backbone, or partial CSI knowledge, otherwise) and if the data are shared over the network. The proposed solutions are base on:

- *Advanced antenna techniques for interference avoidance*. It is well known that adaptive antenna techniques, *e.g.* SDMA, designed for the users in the same cell bring system performance gain. However, it is believed that with effective coordination of antenna patterns the interference among co-band cells can be efficiently managed.
- *Distributed antenna system*. In downlink, several BS can simultaneously transmit forming a Virtual Antenna Array provided the data bits have been distributed through the backhaul and a common codebook is shared. In the uplink, BSs can quantize the signals they receive and perform a centralized decoding. Advanced techniques like distributed compression will be studied in ROCKET to maximize the capacity gain under limited cellular backhaul capacity.
- *Radio resource management*. Depending on the allowed complexity and signalling overhead, multi-cell joint inter-cell radio resource allocation and scheduling may potentially bring large gains. The cells may share the same spectrum (when the interference is weak) or use orthogonal spectrum (when the interference is high). These solutions can be reached as a result of a distributed iterative waterfilling procedure or by adapting the transmission bandwidth between cells from full usage to partial band usage for interference averaging. Moreover, an appropriate formulation of the joint scheduling problem should allow trading between fairness and efficiency, for users in the different cells.

Conclusions

The ROCKET project will design some advanced MAC and PHY techniques including cooperation and flexible spectrum usage in order to achieve a very high throughput per unit area, which is a key criterion to meet future user requirements. Moreover, it must also be noted that these concepts will be supported by hardware prototyping and experimental measurements. For instance, the antenna integration constraints in small form factors like MSs and their effect on the MIMO channel will be investigated by measurements which will feed the algorithmic studies. Another topic investigated by prototyping will be the effect PA non-linearity compensation at both Tx and Rx side to limit the distortion effect on the high order constellations which are needed for high spectral efficiency. Finally, a highly efficient prototyping platform, empowered by state-of-the-art multi-core processors accommodating PHY, MAC and Networking functionality, will be used to prove the computational implementability of key MAC and cooperation concepts.

References

[1] ITU-R Recommendation M. 1645 "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000"

[2] OECD Broadband Portal, http://www.oecd.org/sti/ict/broadband

[3] See Bolloré Télécom trial in Paris www.bolloretelecom.eu and http://www.unstrung.com/document.asp?doc_id=137055

[4] See Sprint-Nextel plans for commercial launch in 2008. http://www.sprint.com and http://www.webwereld.nl/articles/49372/sprint-gets-wimax-soft-launch-underway.html

[5] WiMAX Forum, "Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation", 2006. Available at http://www.wimaxforum.com

[6] ICT-ROCKET project "Reconfigurable OFDMA-based Cooperative NetworKs Enabled by Agile SpecTrum Use (ROCKET)" http://www.ict-rocket.eu/

[7] IST-FIREWORKS Deliverable 2D1 "Cellular Deployment Concepts for Relay-based Systems" 2007. Available at http://fireworks.intranet.gr

[8] P. Marsch and G. Fettweis, "A framework for optimizing the uplink performnce of distributed antenna systems under a constrained backhaul," in Proc. IEEE International Conference on Communications (ICC), Glasgow, UK, Jun. 2007.

[9] P. Marsch and G. Fettweis. "A Decentralized Optimization Approach to Backhaul-Constrained Distributed Antenna Systems" in *Proceedings of the 16th IST Mobile & Wireless Communications Summit (IST summit'07)*, Budapest, Hungary, 01. - 04. July 2007.

[10] M. Kamoun and L. Mazet, "Base-station selection in cooperative single frequency cellular network," in Proc. IEEE Workshop on Signal Processing Advances in Wireless Communications, Helsinky, Finland, Jun. 2007.

[11] World Radiocommunications Conference 2007 (WRC'07) Provisional Final Acts, available at: http://www.itu.int

[12] E2RII white paper. "The E2RII Flexible Spectrum Management (FSM) Framework and Cognitive Pilot Channel (CPC) Concept – Technical and Business Analysis and Recommendations" Nov 2007. http://e2r2.motlabs.com.

[13] Wireless World Initiative New Radio - WINNER and Spectrum Issues (W. Mohr, Siemens) Workshop of the SportViews project Brussels, Belgium 6-Dec-06

[14] IST-FIREWORKS Deliverable 4D3 "Detailed Description of Coding and Modulation for L1 Relaying and Cooperative Communications", 1007. Available at http://fireworks.intranet.gr

[15] B. Fette, Cognitive Radio Technology (Communications Engineering). Newnes, 2006.

[16] Klein, O. et al. "Efficient Multi-hop Communication in Beyond 3G Mobile Radio Networks", Proceedings of IST Mobile Summit 2006,Mykonos, Greece, Jun. 2006

[17] Berlemann, L. et al. "Multimode Communication Protocols Enabling Reconfigurable Radios" EURASIP Journal in Wireless Communications and Networking, Special Issue: "Reconfigurable Radio for Future Generation Wireless Systems" pages 390-400, Aug. 2005

[18] 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.

[19] S. Cho, et al., "Hard Handoff Scheme Exploiting Uplink and Downlink Signals in IEEE 802.16e Systems" in Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd. 2006. ISBN 0-7803-9392-9. ISSN 1550-2252.

[20] S. Simoens, O. Muñoz, J. Vidal "Achievable Rates of Compress-and-Forward Cooperative Relaying on Gaussian Vector Channels", *Proceedings of IEEE ICC'07*, Jun. 2007.

[21] B. Rankov, A. Wittneben “Spectrally Efficient Signaling for Half-Duplex Relay Channels” Asilomar Conf. on Signals, Systems and Computers, Oct. 2005.