Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2009, Article ID 475281, 14 pages
doi:10.1155/2009/475281

Research Article

Dynamic Resource Assignment and Cooperative Relaying in Cellular Networks: Concept and Performance Assessment

Klaus Doppler,[1] Simone Redana,[2] Michał Wódczak,[3] Peter Rost,[4] and Risto Wichman[5]

[1] *Radio Communication CTC, Nokia Research Center, Itämerenkatu 11-13, 00180 Helsinki, Finland*
[2] *Radio Systems, Research & Technology, Research, Technology and Platforms, Nokia Siemens Networks GmbH & Co. KG, St. Martin Strasse 76, 81541 Munich, Germany*
[3] *Applied Research, Telcordia Technologies, Telcordia Poland Sp. z o.o., ul. Umultowska 85, 61-614 Poznań, Poland*
[4] *Vodafone Chair Mobile Communications Systems, Technical University of Denmark, Helmholtzstr. 10, 01069 Dresden, Germany*
[5] *Department of Signal Processing and Acoustics, Helsinki University of Technology, P.O. Box 3000, 02015 TKK, Finland*

Correspondence should be addressed to Klaus Doppler, klaus.doppler@nokia.com

Received 18 February 2009; Revised 19 May 2009; Accepted 1 July 2009

Recommended by Mischa Dohler

Relays are a cost-efficient way to extend or distribute high data rate coverage more evenly in next generation cellular networks. This paper introduces a radio resource management solution based on dynamic and flexible resource assignment and cooperative relaying as key technologies to enhance the downlink performance of relay-based OFDMA cellular networks. It is illustrated how the dynamic resource assignment is combined with beamforming in a macrocellular deployment and with soft-frequency reuse in a metropolitan area deployment. The cooperative relaying solution allows multiple radio access points to cooperatively serve mobile stations by combining their antennas and using the multiantenna techniques available in the system. The proposed schemes are compared to BS only deployments in test scenarios, which have been defined in the WINNER project to be representative for next generation networks. The test scenarios are well defined and motivated and can serve as reference scenarios in standardisation and research. The results show that the proposed schemes increase the average cell throughput and more importantly the number of users with low throughput is greatly reduced.

1. Introduction

Mobile users in next generation communication systems are expecting seamless coverage with a guaranteed Quality of Service (QoS) to allow for a similar user experience as provided by today's broadband internet connections. This causes a high spectrum demand of approximately 100 MHz to support high aggregate data rates of up to 1 Gbit/s, which will only be available at frequencies higher than 2 GHz. The World Radio Conference 2007 has, for example, identified 200 MHz at 3.4 GHz for IMT systems. The high bandwidth and carrier frequencies together with regulatory constraints on the transmission power will limit the range for broadband services. Thus, many small cells are required for contiguous coverage of areas with high traffic density.

In-band relays are seen as a cost efficient way to extend the high throughput coverage of next generation mobile networks. In [1] it was shown that deployments based on in-band relays can increase the high bit rate coverage at the cell border; thereby providing the means to balance the capacity within the cell and increase the coverage area. Relays as part of infrastructure based networks are currently standardised in the Technical Specification Group j (TSG j) of IEEE802.16 [2] and it is currently a study item in 3 GPP [3].

The main focus of this paper is on the performance gain in the downlink of cellular relay networks compared to base station (BS) only deployments in test scenarios that are foreseen for next generation cellular networks. We propose two key radio resource management techniques to exploit the full potential of relay enhanced cellular OFDMA networks: dynamic and flexible resource assignment in a relay enhanced cell and cooperative relaying. We have developed these techniques during five years (2003–2008) of extensive research on cellular relay networks within the European research project WINNER [4]. The dynamic resource assignment adapts to changing user and traffic densities and it is flexible enough to be applicable to deployment scenarios ranging from wide area deployments to local area office deployments. In particular we show how to adapt the dynamic resource assignment to a wide area deployment which utilizes a grid of beams at the base station and to a metropolitan area network utilizing soft-frequency reuse for interference coordination. Our cooperative relaying proposal allows the cooperating radio access points (base station or relay station) to utilize any multiantenna technique used by the system to jointly serve users.

We present numerical evaluation results on the achievable downlink gains from dynamic resource assignment and cooperative relaying compared to BS-based deployments. The numerical results show the final assessment results in a wide area, a metropolitan area, and indoor test scenarios. The results are based on an extensive set of system level simulations after several iterations and refinements during the course of the last three years. Next to the results we describe and motivate the used relay deployments in a wide area, metropolitan area, and an indoor test scenario. We have defined these relay test scenarios in WINNER and they have been contributed to the guidelines by ITU-R for evaluating candidate radio interface technologies for IMT-Advanced [5].

The remainder of this paper is organized as follows. In Section 2 we give an overview on related work. In Section 3 we present the test scenarios for a metropolitan area (Manhattan grid), a wide area (hexagonal grid), and a local area (office environment) relay deployment. In Section 4, we outline the proposed dynamic resource assignment for relay enhanced cells and illustrate its application to the test scenarios. Further, we discuss different flow control mechanisms and introduce our cooperative relaying concept as an add-on to single-path relaying. Thereafter, we present in Section 5 the performance assessment results obtained by system level simulations for the proposed dynamic resource assignment and cooperative relaying in the aforementioned test scenarios.

2. Related Work

The main focus of this paper is on the downlink system performance of a cellular relay network. There is few related work in this area and the results have been obtained with very different assumptions, that is, they are typically not directly comparable. Some of the results where obtained for relaying scenarios where the relay station (RS) transforms a non-line-of-sight (NLOS) base station-mobile station (BS-MS) link into two line-of-sight (LOS) BS-RS and RS-MS links. The BS-RS links can be planned in a cellular network for stationary RSs and the probability of an LOS BS-RS link is increased. However, the MSs can be located anywhere in the cell and the probability of LOS to the BS should be at least the same or even higher than to the RS because the BS is typically deployed higher than the RS. Thus, in order to enable a fair comparison the properties of the BS-MS and RS-MS links should only depend on the deployment. In addition these papers consider all the interfering links to be NLOS, that is, the resulting Signal-to-Interference and Noise Ratios (SINRs) for the RS-MS links are too high. In our studies we did not make such assumptions to ensure a fair comparison.

The downlink performance of a multicell WINNER network in a wide area scenario has also been studied in [6]. Under the assumption of an LOS BS-RS and RS-MS link and NLOS BS-MS and interfering links the saturated throughput of the relay deployment is 25% higher in the relay deployment compared to the same deployment without relays. However, this paper does not apply the dynamic resource assignment proposed in this paper and thus higher gains are expected under these assumptions.

The IEEE 802.16j has issued a draft standard [7] and first performance results for the downlink of such a system are available. In [8] a scenario with 14 RS added to each BS in a macrocellular deployment with a cell radius of 1 km is studied. Again an RS transforms an NLOS BS-MS link into two LOS BS-RS and RS-MS links. Under this assumption the relay deployment increases the downlink capacity of the cellular network by more than 100%. The results in [9] indicate that for relays that do not extend the coverage area of a BS (transparent relays in IEEE 802.16j) the performance gains are below 5%. In [10] different reuse pattern and path selection rules have been studied. The results show that a macrocellular relay deployment can serve up to 90% more users than a BS-based deployment. However, this comparison does not consider sectors at the BS and shadow fading as well as fast fading is not modeled. Further, the RS transmission power is only 3 dB less than the BS transmission power, which would not result in significant cost savings due to the use of relays.

Another set of assessment results for a WiMAX relay deployment in a metropolitan area is available in [11, 12]. Unfortunately, there is no comparison with a BS only deployment but the results show significant gains from using directive antennas. In this work it is assumed that the BSs and RNs are deployed at street crossings with directional antennas covering the streets leading to the crossing. In practical deployments it will be hard to deploy a radio access point at street crossings and therefore our work focuses on a deployment in the streets which is also recommended by 3 GPP in [13] and similar to [11, 12] we also utilize directive antennas (sectors) at the BS. Secondly, the previous work in the metropolitan area has focused on outdoor users in the street whereas we consider also users inside the building blocks that typically account for most of the traffic in a cellular network.

In addition to multicell studies, several aspects of the cellular downlink of OFDMA systems have been studied for a single cell. In [14] the OFDMA resource allocation for a single relay enhanced cell with multiple users and a maximum C/I scheduler is analyzed. In these studies the relay deployment achieves 15% higher data throughput and the outage probability is reduced from 30% to 20%. In [15] it is shown that the optimization of the subframe duration (RS transmits to MS/RS receives from BS) together with

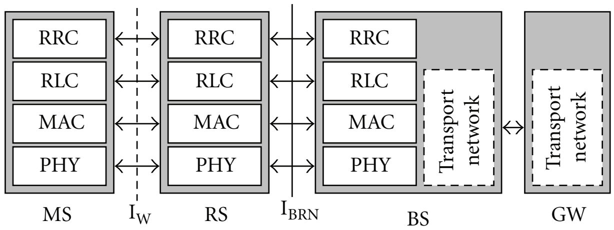


Figure 1: RSs within the cellular network, the control plane.

subcarrier allocation improves the overall cell throughput compared to subcarrier allocation only as proposed in [16]. These single cell results confirm that the subframe duration should be flexible as proposed by our dynamic resource assignment.

System performance results of relay-based deployments for the cellular uplink for the WINNER system can be found in [17] and for IEEE 802.16j in [18]. Early performance assessment results for cellular relay networks that are not based on OFDMA can be found, for example, in [19] for the integrated Cellular Ad hoc Relay System, in [20] for mobile relays, and in [21] for a 1xEVDO system enhanced by relays.

The results presented in this paper are the final assessment results of the relay-based system developed in WINNER Phase II [22]. We have presented parts of the concept and early performance results in [23–27].

Differently to our wide area results in [23] these are the first results that have been obtained in a dynamic scenario and we compare the performance of a relay deployment with dynamic resource sharing to a BS only deployment. In addition we utilize the connection-based scheduling flow control scheme that we have presented in the context of WiMAX in [24]. The results in [26] have been obtained for relays deployed above rooftop and with more relays per sector. Increasing the amount of relays increases the benefits due to cooperative relaying but it also increases the costs of the deployment.

The metropolitan area results in [25] did not utilize soft-frequency reuse for the BS only scenario and the power masks have been updated for the relay scenario considered in this paper. Further, we utilize the interference aware scheduling scheme designed for soft-frequency reuse that we evaluated for a BS only deployment in [28]. This is also the first time that we present results for outdoor users and show the effect of a simple flow control on the system performance.

The local area results in [27] compared different relay deployment options whereas now we compare the expected user throughput of a relay deployment to a BS only deployment.

3. Relay Properties and Test Scenarios

The design of a radio resource management scheme for relay-based systems depends on the properties of the relays and on the deployment of the relays. In addition the multiantenna techniques utilized in the system have to be taken into account. Therefore we introduce and motivate first the main properties of the relays and the relay deployments considered in our work. The main motivation to deploy relays is to save costs while reaching a similar performance as less dense BS only deployments or to increase the performance of a BS deployment cost efficiently by adding relays. Hence, most of the following design choices are motivated by cost considerations.

In our test scenarios we allow an intelligent deployment with favorable propagation conditions between the base station (BS) and the relay station (RS), for example, line-of-sight (LOS) to the BS. As a consequence the quality of the BS-RS link can be very different from the RS-MS link. Therefore, we consider only decode-and-forward relays (operating up to OSI layer 3), which can take advantage of dynamic resource allocation and adaptive transmissions with different modulation and coding schemes when receiving and forwarding data.

The intelligent deployment assumption is based on cost comparison studies of relay based and BS only deployments. For intelligent relay deployments studied in [29, 30] RSs are already cost efficient if the costs are 88% of the costs of a micro-BS. Without intelligent deployment the RS cost should be only 6.5% of the BS costs [31].

The number of RSs per BS is an important design parameter that affects both the costs and the performance of the relay network. We have limited the number of RSs to three per BS sector based on the result curves in [29] which do not suggest more than 4 RSs per BS in a scenario similar to the one considered in our work.

To keep the size of RSs small we assume in all scenarios a limited transmit power for RSs and a maximum of two antennas. Small RSs that do not require shelter, cooling, and backhaul connection increase the deployment flexibility and allow, for example, a deployment on lamp posts. Thereby the site acquisition and site rental costs can be reduced even compared to a micro- or pico-BS. According to cost studies in [32] site rental and the cost of the transmission line account for more than 60% of the overall costs of a micro-BS over 10 years.

Finally, we require that adding a RS to the network does not increase the cost of an MS. This is achieved by a RS that provides an identical interface towards an MS as a BS, that is, the MS does not need to distinguish between RS and BS and both are referred to as radio access points. Further, we focus on in-band relays that do not require additional bandwidth. The resulting multihop cellular system architecture is illustrated in Figure 1 [33]. A Relay Enhanced Cell (REC) is formed out of a BS together with its associated RSs.

Our test scenarios are primarily designed and optimized for two hops (BS-RS-MS) in order to achieve a high performance in terms of throughput and delay. Further, we assume a tree topology to avoid the overhead from complex routing protocols. In the rare case of node failure the RS can autonomously connect itself to another radio access point in its range.

For base station-based deployments the hexagonal grid cell layout with variable intersite distance and the Manhattan grid following the UMTS 30.03 recommendations [13] have been accepted as evaluation scenarios in standardization and research. However, no such widely accepted scenarios exist for relay deployments and the results of different research groups are not comparable.

In the following we present relay test scenarios for three typical deployments of future wireless communication systems: a wide area scenario that provides base urban coverage based on a hexagonal cell layout, a metropolitan area scenario based on microcells deployed in a Manhattan grid, and a local area office scenario. Both the wide area and the metropolitan area scenarios cover the important case of an operator that wants to upgrade an existing UMTS network and to reuse the existing BS locations. The properties of the MS are the same in all scenarios (see Table 4 in Appendix A).

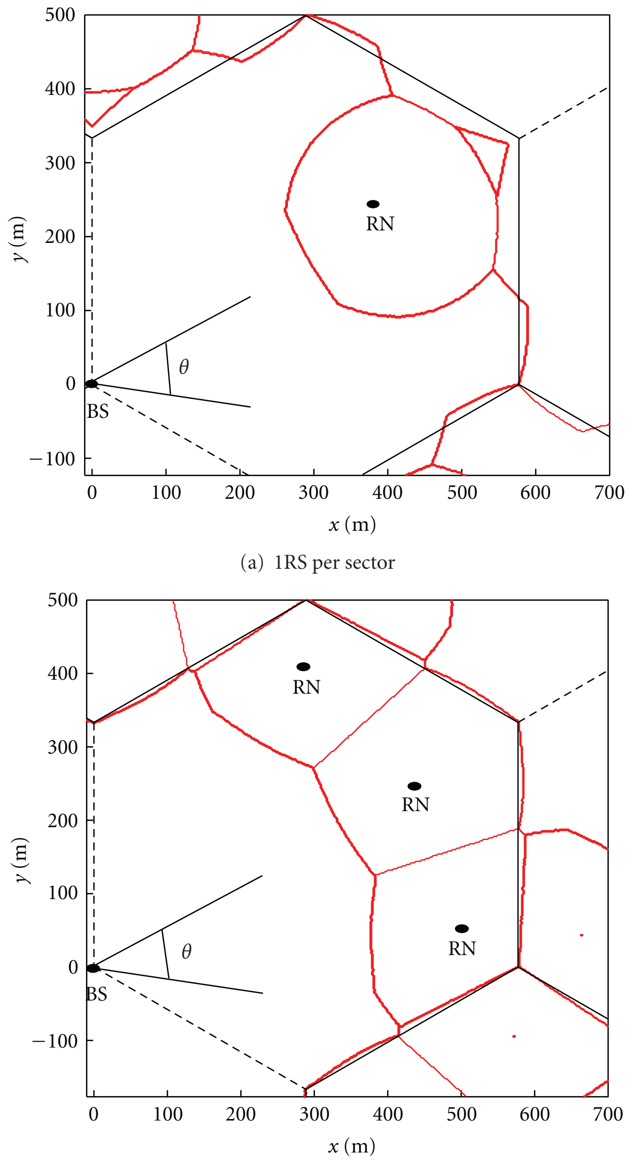
All three test scenarios use path loss and channel models developed in Phase II of the WINNER project. The properties of the channel model and a comparison to other models can be found in [34]. The path-loss equations and the corresponding channel models can also be found in [35]. Since [35] offers several possible path-loss models for each link type we state the path-loss equations used in the test scenarios in Appendices B, C, and D.

3.1. Wide Area Test Scenario. The wide area test scenario is an urban macrocellular deployment. It aims at providing ubiquitous coverage in an urban environment resulting in rather large cells, having a radius up to several kilometers. Base stations (BSs) are consequently expected to provide high power outputs, in each of the three sectors, equipped with four antennas. All BSs are deployed above rooftop ($h_{BS} = 25$ m), possibly requiring additional masts for their installation. This implies that the site selection and rental costs will probably be dominant with respect to the other costs such as the backhaul infrastructure. We further consider RSs which are deployed below rooftop ($h_{RS} = 5$ m) with a single antenna and a significantly lower output power in order to keep costs low and allow for a flexible deployment of multiple RSs per sector. For the same reason the RS is equipped with a single antenna.

We distinguish between a carefully planned RS deployment with a high probability of line-of-sight (LOS) and a not carefully planned RS deployment without LOS to the BS. For both cases and the BS-MS link we assume an urban macrocell model whereas we assume for the RS-MS a non-LOS (NLOS) microcell model (see Appendix B for details).

The cells form a regular grid with a hexagonal layout and an intersite distance (ISD) of 1000 meters. We study this scenario with three RSs per sector according to the deployment in Table 1. It provides, as shown in Figure 2, a good coverage for MSs at the cell border. Moreover, we consider also the scenario with only one RS per sector (also shown in Figure 2) for comparison purpose. The exact RS deployments are outlined in Table 1 for both scenarios.

3.2. Metropolitan Area Test Scenario. The metropolitan area test scenario is an urban micro-cellular scenario modeled by a two-dimensional Manhattan grid consisting of 12 × 12 streets (width 30 m) and 11 × 11 buildings (200 m × 200 m block size). The BS deployment follows the UMTS 30.03 recommendation [13] with 73 BS deployed below rooftop level (10 m height) and placed in the midpoint between two crossroads. Two sectors are formed with bore-sight along the street direction and one antenna per sector. The added relays extend the coverage area of these BSs and distribute the cell capacity more evenly.



(a) 1RS per sector

(b) 3RS per sector

Figure 2: Coverage area for BS and RS in wide area test scenario.

Table 1: RS deployment in the wide area test scenario.

Num RSs per sector	BS-RS distance (m)	Θ (deg) (relative to sector broadside direction)
1	440	0
3	500	−24, 0, 24

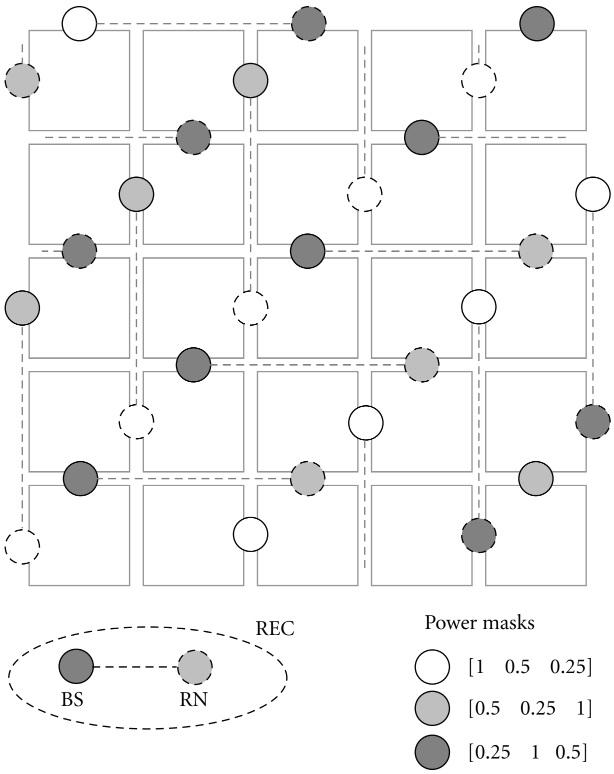


Figure 3: Sketch of metropolitan area cell layout with relay stations and assigned soft-frequency reuse power masks.

A single RS (5 m height) is added to each BS site in the midpoint between two BSs, as depicted in Figure 3. Thereby the number of radio access points is doubled. Adding a second relay per BS site increases the cell throughput only slightly and does not justify the additional costs [25]. The RSs are equipped with two antennas, a directional antenna to communicate with the serving BS and an omnidirectional antenna to serve its MSs. The power masks assigned to each BS and RS in Figure 3 are used by an interference coordination scheme based on soft-frequency reuse which is described in Section 4. The transmit power of the RS is 7 dB lower than the transmit power of the BS to enable a smaller physical size.

A LOS link is assumed for nodes in the same street and a NLOS link for nodes in different streets and MSs are located inside a building or in a street. Details of the propagation model and additional simulation parameters can be found in Appendix C.

3.3. Local Area Test Scenario. The local area test scenario is defined as an isolated hot-spot-like indoor area with high user density where the users are either stationary or slowly moving. It is characterized by high shadowing and considerable signal attenuation due to the existence of rooms separated by walls. As a result of the isolated characteristics the interference is much lower compared to the previous two scenarios. The scenario consists of one floor (3 m high) in a building with two corridors (5 m × 100 m) and 40 rooms (10 m × 10 m).

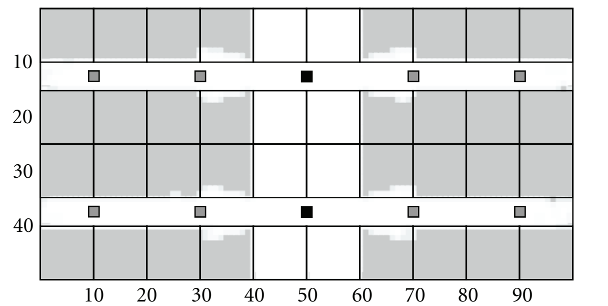


Figure 4: Local area scenario with two BSs (dark gray) and four relay stations (light gray) to assist each BS.

A deployment with two single antenna BSs (dark gray nodes) is presented in Figure 4. They are located in the middle of the corridors, halfway from the left/right side of the building. Each of them is assisted by four single antenna RSs (light gray nodes): two on the left and two on the right side, respectively (i.e., 10, 30, 70, and 90 meters from the left or the right side of the building) as depicted in Figure 4. All the area marked with gray color benefits from the use of (cooperating) RSs.

A LOS or NLOS office propagation model is employed depending on the presence of walls between the BS, RSs, and MSs. Details of the propagation model and additional simulation parameters can be found in Appendix D.

4. Radio Resource Management in Relay Enhanced Cells

Relays add additional degrees of freedom to the radio resource management of a cellular system. The RS can act as a BS to serve its MS or as an MS to receive data from the BS. The coverage area of an RS is lower than for a BS due to the lower transmit power and different deployments. Nevertheless, they should be integrated and evaluated together with the interference coordination and multiantenna techniques utilized in the network. On the other hand the cooperation of multiple radio access points is easier in a relay enhanced cell than between BSs since the BS can act as a coordinating node in the resource allocation for cooperatively served users.

In the following we propose the following radio resource management techniques for relay enhanced cells: dynamic resource assignment, flow control for multihop connections and cooperative relaying as an add-on to single-path relaying.

4.1. Dynamic Resource Assignment. A fixed and static resource assignment will not allow to exploit the full potential of relay-based deployments since the relay deployments can have very different properties as illustrated in Section 3. Therefore, we propose that the BS flexibly assigns parts or all of the available system resources to itself and to each RS in the relay enhanced cell. In particular the BS assigns the frames in which the RS communicates with the BS (act as an MS) or serves its MS (act as a BS). Further, it assigns the OFDMA resource units (chunks) that the RS can use in the frames for which it acts as a BS. The assigned resources are then available for autonomous scheduling at each individual radio access point. Figure 5 illustrates an example resource allocation for a BS with three RS in its cell.

The actual resource assignment strategy depends on the utilized interference coordination and multiantenna techniques. In the wide area test scenario beamforming has been shown to be an effective way to improve the cell capacity [37]. We propose to coordinate the interference from the subcells formed by the BS to the subcell formed by RSs by using at the BS beams with low interference to the RS subcell for resources that have been assigned to the RS. The amount of resources for the RS is dynamically adjusted depending on the traffic and interference situation. We refer to this approach as Dynamic Resource Sharing (DRS) [38]. DRS uses logical beams which can be seen as a dynamic version of sectors. The Dynamic Resource Sharing (DRS) acts in three steps: the creation of the beams, grouping of the beams, and the actual resource assignment [38]. For the assessment results presented in Section 5 we utilize the resource assignment that we proposed in [23] which aims to achieve the maximum possible cell throughput by allocating an OFDMA resource unit (chunk) to the group of beams that can reach the highest total rate.

In the metropolitan area scenario we study an interference coordination scheme based on soft frequency reuse. It assigns power masks (in the frequency domain) to neighboring radio access points to coordinate the mutual interference. Thereby, soft frequency reuse enables frequency reuse one and at the same time each radio access point has high power resources with reduced interference available to schedule MS located at the border area. Soft frequency reuse is better suited for the metropolitan area than beamforming because the radio signal propagates very well in the street canyons making it difficult to separate different beams. Further, interference coordination is mainly needed at street crossings and in the border area between radio access points, whereas the border area is smaller than in a wide area deployment.

In the local area scenario we make use of the fact that the BSs and RSs located in different corridors are separated by at least three walls which can be perceived as a natural means of suppressing interference. Due to the physical separation, sharing of the same resources may be possible for multiple transmissions. In cases where it is not possible to share the resources, the users are either served cooperatively by multiple radio access points or exclusive resources are assigned.

Table 2 summarizes the essential elements of the resource assignment. The MS does not need to perform additional measurements to support the resource assignment. The BS uses the received signal strength from neighboring radio access points (BS or RS) reported by the MS as an input, which are anyway required for handover purposes. Please note that the logical beams are a dynamic version of sectors

Table 2: Example of essential elements of resource assignment scheme.

Resources to be assigned	Frames in superframe where RS serves MS/communicates to BS, chunks assigned to RS, power mask to be used for chunks
Granularity of resources	Group of four OFDMA resource units (chunks) in the frequency domain, TDMA frame in the time domain (0.7 ms)
Measurements/information related	
Measurements required	Received signal strength of neighboring radio access point sector (beam)
Who performs measurements	MS
Additional information	Estimate of required chunks to serve MS
How often	New measurement and message every 100 ms
Who collects it	Serving radio access point
Who uses it	BS in REC
Resource assignment message	
Content	Power mask (MA), frames assigned to serve MS in superframe, chunks assigned within the UL/DL frames to the RS

and therefore also measurements for the logical beams will be available.

Real world deployments are not as regular as the presented test scenarios and due to the small size of the subcells formed by BSs and its RSs the traffic density can vary significantly in these subcells. The proposed dynamic resource assignment scheme offers sufficient flexibility to adapt better to real world situations than a static resource assignment.

4.2. Flow Control. In WINNER we propose a distributed scheduling, that is, the BS assigns resources to itself and the RSs in the relay enhanced cells but it does not centrally schedule the transmissions to the MSs. The RSs can then independently allocate these resources to its associated MSs. Thus, frequency adaptive transmissions and multiantenna transmission schemes can be supported without forwarding channel state information, precoding weight feedback, and so forth to the BS. This decision can be justified by the results in [14, 15] which indicate a performance loss of less than 10% compared to a centralized scheduler even without considering the signaling overhead for a centralized scheduler.

However, when utilizing distributed scheduling the BS should be aware of the buffer status of each MS or flow at the RS. If it forwards too much data to the RS eventually the buffer of the RS will overflow and if it forwards too

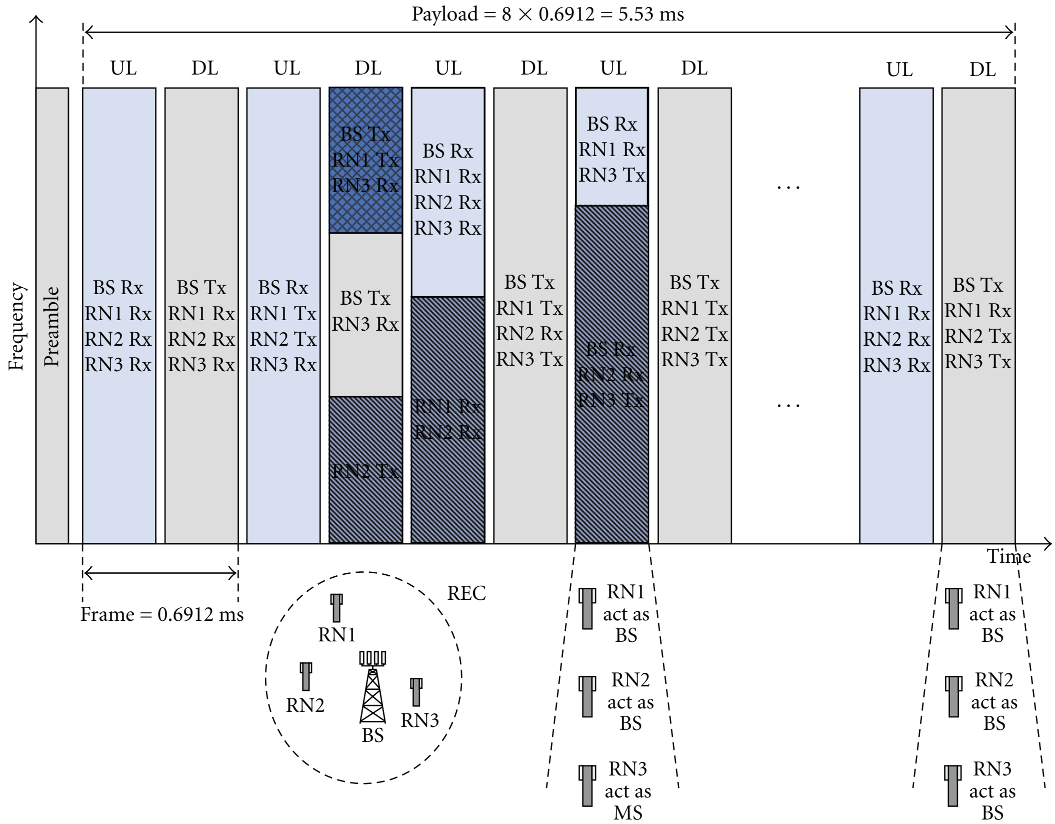


Figure 5: Example allocation of a superframe using the Flexible Resource Assignment scheme in a relay enhanced cell with three relays (RSs). The super-frame consists of a preamble and an 8-frame payload following the WINNER system specifications [36]. The Base Station (BS) allocates (a part of) the resources to the RSs, the RSs independently schedule their associated MS within their allocations when acting as BS.

little data the MS will be starved. Even if the buffer at the RS is large enough to store all the data for the MS, the resources on the BS-RS link have been wasted when the MS performs a handover to another RS or BS. In our work we have considered two different approaches to flow control: connection-based scheduling (CbS) and stop-and-go signaling. The results in Section 5 show that both schemes are well suited for the considered deployments with a maximum of two hops.

The CbS is a resource request and allocation strategy proposed in [24] for controlling the resources and delays of multihop communications with different numbers of hops. Each RS requests to the BS not only the needed resources for data transmission on the access link between the RS and the MSs but also on the multihop links from/to the BS. Every RS computes the resources required for each end-to-end connection served by the RS instead of only the next link towards the destination. The BS collects the resource requests and grants resources on each hop for each connection (uplink and/or downlink) between the BS and each RS.

The stop-and-go flow control requires less signaling than the CbS but CbS is better suited for deployments with more than two hops. It depends on the rate of the RS-MS link. The RS sends a stop signal for an MS to the BS when the queue size for the MS exceeds ι. The queue size ι depends on the current channel quality of the RS-MS link and is calculated as

$$\iota = nR_{\text{fullBw}}, \tag{1}$$

where R_{fullBW} denotes the predicted rate (based on channel quality feedback) when the MS is assigned the full bandwidth and n is a parameter that can depend on the number of users served by the RS and the amount of frames where the RS serves its MSs. For the numerical assessment results in the metropolitan area we have used a fixed parameter $n = 2$ and compare the performance of the proposed flow control to a scenario without flow control.

4.3. Cooperative Relaying as Add-On to Single-Path Relaying. Next to the flexible resource assignment, we propose cooperative relaying to further enhance the capacity of a relay enhanced cell. In the DL of single-path relaying, the data is first transmitted from the BS to the RS and then the RS forwards this data to the MS. (We refer in the following to noncooperative relaying as *single-path relaying*, because only a single transmission path between source and destination is exploited.) To gain on large-scale spatial diversity, most cooperative relaying protocols proposed in literature, for example, [39–41] benefit from a combination of the transmissions in two phases, first from the BS and then from the RS. An overview and classification of different cooperative relaying protocols can be found in [42–44].

As the transmission from a BS is received by the MS and the RS, dedicated multiantenna techniques (beamforming and other space division multiple access (SDMA) algorithms) can be applied only partially, because *one* stream is only optimized for *one* destination. Furthermore, as we assume an intelligent deployment, the achievable data rate on the BS-RS link is likely to exceed the data rate on the RS-MS links. However, to enable cooperation on the physical layer the same modulation and coding scheme or only a limited set of specialized and sophisticated modulation and coding schemes can be used.

Thus, we do not only consider cooperative relaying that exploits large-scale spatial diversity but we investigate mainly cooperative relaying, where multiple radio access points form a Virtual Antenna Array (VAA) [45]. Any multiantenna transmission technique, including spatial multiplexing, can then be applied, for example, to the BS antennas augmented by the antennas of an RS. In Section 5 we present results for a cooperative multiuser MIMO relaying scheme that we proposed in [26]. It utilizes distributed LQ precoding which has been introduced for cooperating BSs in [46] and a dirty paper coding technique as proposed in [47].

In our cooperative relaying proposal the first common node in the tree topology schedules the cooperative transmission. Thus, in a network that is limited to two hops, the BS allocates resources to all cooperative transmissions in a similar way as in single hop networks using similar feedback information. The BS then sends the resource allocation and the selected transmission mode (MIMO transmission scheme, precoding weights, modulation and coding scheme for different streams, etc.) together with the data to the RS(s). Both BS-RS cooperation and RS-RS cooperation are supported. Figure 6 illustrates restrictions at the RS resulting from cooperatively served MSs. The RS has to take these restrictions into account when allocating resources to the MSs served solely by the RS within the resources assigned from the BS.

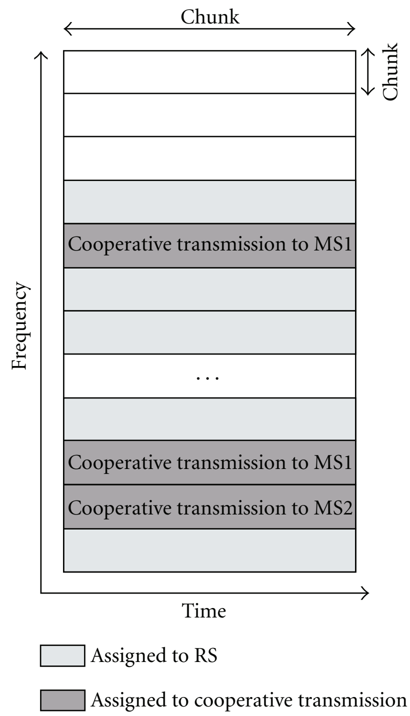


Figure 6: Scheduling restrictions at the RS. The RS receives resource allocation for cooperative transmissions from the BS. Together with the flexible resource assignment this restricts the resources the RS can use to schedule noncooperative transmissions.

When calculating the precoding weights for a cooperative (multiuser) MIMO transmission scheme the channel matrices of all the cooperating nodes have to be forwarded to the BS and the precoding weights have to be transmitted to the RS before the cooperative transmission. Due to this high amount of data which has to be communicated between BS and RS(s), MIMO cooperative relaying is more affected by a limited BS-RS link capacity than single path relaying. Hence, the proposed MIMO cooperative relaying solution requires a high capacity BS-RS link which can be guaranteed by a line-of-sight assumption between BS and RSs.

The highest gain from cooperative relaying is obtained if the signals received from the cooperating radio access points are of similar strength. Therefore we base the decision which radio access points (BS or RS) should form the VAA on the received signal strength reported by the MS and RS. In particular we propose the use of a static version of the REACT algorithm [48]. The original algorithm was developed for mobile ad hoc networks with relays and due to the fact that in the scenario under investigation the RSs are located at fixed positions there is no need to perform periodic neighbor discovery and topology recognition. The static version of REACT is executed by the BS and exploits information about power levels of the signals received by MSs from different radio access points (BS or RS) as well as the power levels of the signals received by RSs from the BS. Thus, the BS has a good overview of the topology to select the cooperation type.

Next to data transmissions the MSs have to receive control information. In our cooperative relaying proposal the control information is not transmitted cooperatively but each MS has a serving RAP which can be the BS or an RS. In either case, the serving RAP performs retransmissions, transmits the broadcast channel, receives feedback from the MS, and signals the resource allocation to the MS.

4.4. Applicability to IEEE802.16j. The IEEE802.16j draft standard [49] allows already a dynamic resource assignment in the time domain by adjusting the duration of the relay zone but no mechanism has been standardized for the frequency domain. In the case of dynamic resource sharing the resource assignment in frequency domain can simply be done by signaling chunks (subchannels in WiMAX terminology) that should not be used by an RS. For soft-frequency reuse, in addition the power mask to be applied for chunks has to be signaled. Thus, with small additional signaling the 802.16j standard can support the flexible resource assignment proposed in this paper.

The draft 802.16j standard [49] also specifies the possibility for cooperative BS-RS transmissions. It mentions two basic possibilities: *cooperative source diversity* (repetition coding) and *cooperative transmit diversity* established through distributed space-time block coding (STBC) and a combination of both. We propose a much more flexible scheme that supports also RS-RS cooperation and any MIMO scheme that is used in a system. Thus, major additions would be required to the standard in order to support our concept.

5. Numerical Results

In this section we present performance assessment results for the dynamic and flexible resource assignment and cooperative relaying in a multicell OFDMA network. We compare the performance of relay deployments to BS only deployments in the test scenarios presented in Section 3. For the metropolitan area and the cooperative relaying results in the wide area we assume two antennas at the RS and a single antenna otherwise.

All results have been obtained in system level simulations using the link to system level mapping of [50] and parameters from the WINNER system. Table 5 in Appendix A presents the main parameters of the FDD physical layer mode utilized for the wide area assessment of DRS and the TDD physical layer mode of the WINNER system which has been used in all other scenarios. For both modes an overall system bandwidth of 100 MHz was chosen in order to meet the peak data rates that were established as research targets for systems beyond IMT-2000 [51].

All simulations have been performed with a full buffer traffic model and the MSs are selected for scheduling at the BS and the RS by a round robin scheduler. In the metropolitan area we additionally utilize the channel aware scheduling in the frequency domain that we proposed in [28]. The MSs are associated with the strongest radio access point (BS or RS) in the case of single-path relaying. In the case of cooperative relaying they are jointly served by BS and RS if the received signal power of the two radio access points is within 20 dB. RS-RS cooperation is not considered in this scenario since the RSs do not have large overlapping coverage area.

The results have been obtained for the center cell in the wide area scenario and for two center cells in the metropolitan area. In both cases the center cells were surrounded by 2 tiers of interfering cells. In the metropolitan area, the radio access points (BS and RS) have been divided into three groups and a relative power level pattern has been assigned to each group, as illustrated in Figure 3. The absolute power levels depend on the maximum transmit power of the radio access point. The power mask levels have not been optimized but we believe they are reasonable choices.

The results in Table 3 compare the average cell throughput and the fifth percentile of the user throughput cumulative distribution of a BS only deployment to a relay-based deployment in the wide area and metropolitan area test scenario with different radio resource management options.

5.1. Dynamic Resource Allocation in Wide Area Test Scenario.

In this analysis the deployment positions of RSs are not optimized with respect to the propagation conditions to the BS. Therefore an NLOS model is assumed and the path-loss between BS-RS is calculated as in (B.2).

The wide area results on DRS in Table 3 show that the DRS outperforms the BS only deployment. By utilizing this approach the cell throughput is increased by 25% with only one RS per sector and by almost 50% assuming 3 RSs per sector. Table 3 also shows results for a Fixed Resource Partitioning (FRP) without coordinating the beams at the BS with RS transmissions. The static resource partitioning is based on the following considerations. The relay coverage area is about one forth of the sector area, as shown in Figure 2. The throughput of the relay link (BS-RS) is assumed to be twice the average throughput of the RS-MS links. Further, the throughput per user in the coverage area of a BS is assumed to be the same as in the coverage area of an RS. To avoid interference the BS does not serve its MSs while the RS serves its MSs. Hence, the resource demand for the different links was estimated to be 6/9 for the BS-MS links, 1/9 for the BS-RS links, and 2/9 for the RS-MS links. With this static resource partitioning we can observe that the average cell throughput is reduced by 30% compared to the BS only scenario. Thus, without properly assigning the resources inside the cell the potential benefits of relaying are lost and the performance might even degrade.

5.2. Soft Frequency Reuse in Metropolitan Area Test Scenario.

In the metropolitan area we compare the performance of a relay deployment using the flexible resource assignment proposed in Section 4 and soft frequency reuse (SFR) to a BS only deployment. These studies assume a slowly changing resource assignment for the studied part of the network which remains constant during the simulated 70 seconds of network operation. This models a flexible resource assignment that adapts to slow variations, for example, depending on the time of the day, and the same assignment is used for all cells in this part of the network.

Table 3 shows the results both for users located indoors and in the streets. The outdoor to indoor coverage of the BS only deployment is limited and adding relays is especially beneficial for users with low throughput in the BS only deployment. As a result the fifth percentile of the user throughput CDF more than quadruples. However, for users in the street the BS only scenario is already interference limited and adding RSs does neither increase the cell throughput nor the fifth percentile of the user throughput CDF.

We allow both the RS and BS to serve its MSs at the same time which achieves significantly better results compared to BS and RS serving MSs in separate frames. The amount of frames within a superframe where the RS is serving MSs depends on the capacity of the BS-RS link and the RS-MS links. As the capacity of the BS-RS link is very high, the best

Table 3: Relative performance of BS only and RS deployment with different resource assignment options in the test scenarios.

Deployment	Resource assignment	Avg. cell cell TP	5%-ile of MS TP
Wide area DRS			
BS only	—	1	—
BS + 1RS	DRS	1.25	—
BS + 3RS	DRS	1.45	—
BS + 1RS	FRP	0.7	—
Metropolitan area indoor SFR			
BS only	Reuse one	1	—
BS only	SFR	1.02	1
BS + RS	FRP separate	0.56	1.18
BS + RS	FRP	1.08	3.12
BS + RS	Best	1.12	3.80
BS + RS	Best + SFR	1.12	4.30
BS + RS	Best + SFR − flow control	1.11	4.18
Metropolitan area outdoor SFR			
BS only	Reuse one	1	1
BS only	SFR	1.03	1.39
BS + RS	FRP separate	0.48	0.30
BS + RS	FRP	0.92	0.67
BS + RS	Best	0.94	0.74
BS + RS	Best + SFR	0.97	0.95

result was achieved when the RS serves its MSs in five out of eight frames. Thus, three out of eight frames are sufficient for the BS-RS communication. Selecting the optimal number of frames for the RS transmission improves the fifth percentile of the user throughput CDF by 38% and the average cell throughput by 4% compared to an assignment where the RS serves its MSs in every other frame. This indicates that the performance of relay deployments strongly depends on the proper balance between the resources spent on the first hop, between BS and RS, and on the second hop, between RS and MS.

We also studied the impact of flow control on the overall performance of the network. For the case without flow control we set the stop limit to 25 Mbit per flow which corresponds to about 8 seconds of data for an MS. Without flow control the average cell throughput decreases by less than 1% and the fifth percentile of the user throughput CDF by 3%. The impact of flow control is rather limited in this scenario since the BSs transmit data to the RSs only in 38% of the frames and RSs are only present in every second sector. The conclusions will likely be different in a scenario with more relays and more than two hops. Especially for more than two hops a flow control based on connection-based scheduling is likely the better option.

5.3. Cooperative Relaying in Wide Area Test Scenario. Cooperative relaying can further enhance the performance of a relay deployment. To evaluate the potential benefits of cooperative relaying we compare the cooperative multiuser MIMO relaying scheme with single-path relaying and a system using only direct links between BSs and MSs (BS only). The path loss for the BS-RS link assumes a careful relay deployment and is calculated as in (B.3).

Figure 7 presents the CDF of the expected user throughput $\Theta(\cdot,\cdot)$. We can clearly observe from the CDF of the throughput that the number of users with low throughput is significantly reduced, compared to a system without relay stations. Besides, we can observe a major performance advantage of cooperative relaying in comparison to single-path relaying. This is of course at the cost of additional signaling and control overhead. Nonetheless, the coordinated and joint transmission of BSs and RSs seems to be a viable option especially in those areas where an MS experiences similar channel conditions to both radio access points.

5.4. Cooperative Relaying in Local Area Test Scenario. In the local area test scenario, we assess the performance of cooperative relaying for the deployment given in Figure 4 [27]. We compare two different possibilities. The MSs are served by the BS or by RS using either single-path relaying (BS-RS-MS) or cooperative relaying (BS-VAA-MS), where a Virtual Antenna Array (VAA) is formed by a pair of cooperating RSs. The RSs forming the VAA are chosen with the use of a static version of the REACT algorithm as described in Section 4.3.

The results were obtained for a fixed modulation and coding scheme based on QPSK modulation and the $(4,5,7)$ convolutional code with the use of the fixed resource assignment in [27]. Further, an AWGN channel model was assumed. The presence of an outdoor network is modeled by setting an average interference power level of -125 dBm per subcarrier.

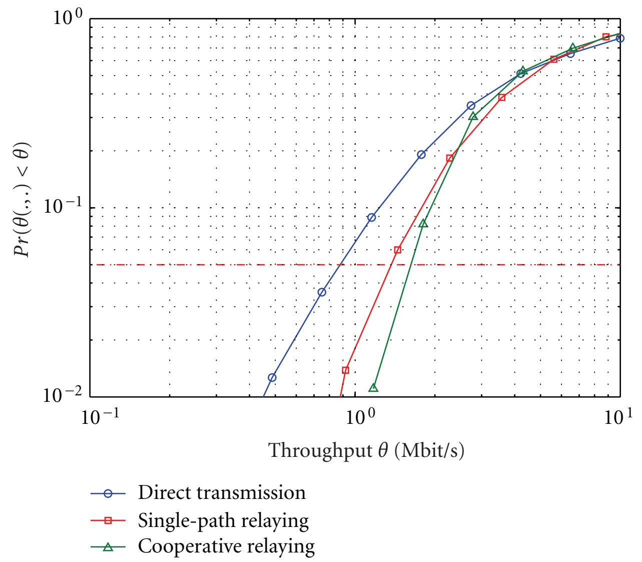


Figure 7: User throughput CDF for cooperative relaying in wide area scenario with 3 RSs per sector.

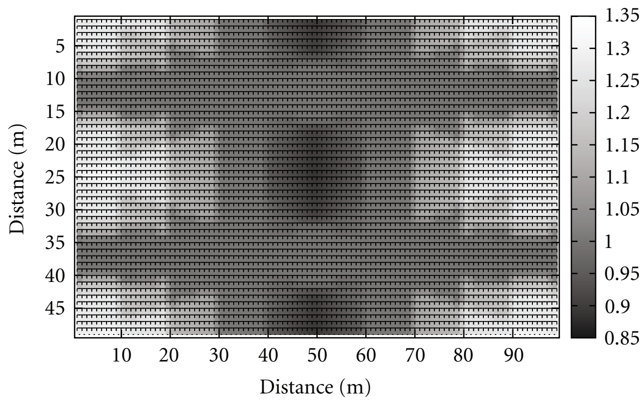


Figure 8: User throughput achieved for cooperative relaying in relation to direct transmission.

The results are depicted in Figure 8 and show improvements of up to 30% for regions where RS-RS cooperation can be applied compared to MSs that are served only by the BS. Analyzing these results one can see that the performance is largely unaffected in the central part of the scenario and in the corridors that can be covered by the BS. However, direct transmission is only advantageous in the central part and nearby the horizontal walls, halfway between the vertical ones, where it offers a gain of 10% over cooperative relaying. As it was already mentioned, the benefits of deploying relays in the local area scenario can be explained by numerous walls providing additional shadowing. Hence, it is advantageous to have additional radio access point. The BSs serve the MSs in their immediate vicinity. The other MSs are served cooperatively and experience a higher throughput.

Table 4: Additional parameters for test scenarios.

Scenario	Wide area	Metropolitan area	Local area
BS tx power per sector	46 dBm	37 dBm	21 dBm
RS tx power	37 dBm	30 dBm	21 dBm
MS tx power	21 dBm	21 dBm	21 dBm
BS antenna	14 dBi	8 dBi	14 dBi
Gain	120°	120°	Omni
RS antenna	9 dBi	14 dBi/7 dBi	7 dBi
Gain	omni	60°/omni	omni
MS antenna	0 dBi	0 dBi	0 dBi
Gain	Omni	Omni	Omni
Noise figure	5 dB	5 dB	7 dB

6. Conclusion

In this paper we presented key technologies that allow to exploit the potential benefits of a relay-based deployment. In particular we introduced dynamic and flexible resource assignment in a relay enhanced cell and cooperative relaying.

Our performance results indicate that a relay based deployment using the proposed resource assignment significantly increases the lower percentiles of the user throughput cumulative distribution function and it improves the cell throughput compared to a BS only scenario. Our results also show that the performance gains are lost, if a static resource partitioning is used.

The cooperative relaying solution utilizes a virtual antenna array formed by the base station and the relay station antennas. Cooperative relaying reduces the number of users with low throughput even further than single-path relaying.

Even though these assessment results have been obtained for WINNER OFDMA parameters, they give also insights on the potential benefits of relays for OFDMA-based cellular systems like WiMAX and 3GPP Long-Term Evolution (LTE). In particular the presented results on dynamic resource assignment are applicable to the IEEE802.16j draft standard [49].

Appendices

A. Additional Simulation Parameters

Table 4 presents selected simulation parameters and Table 5 the OFDMA parameters of the WINNER system in both FDD and TDD mode.

The numerical evaluations have been carried out for a carrier frequency of 3.95 GHz which has not been allocated to IMT systems at the World Radio Communications Conference 2007. Nevertheless, for example, 200 MHz have been allocated between 3.4 and 3.6 GHz and changing the carrier frequency, for example, to 3.55 GHz will not significantly change the results or our conclusions. The 5 GHz carrier frequency chosen for the local area is close to the license exempt Universal-Networking Information Infrastructure (U-NII, 5.15–5.35 GHz) band and the upper Industry Science and Medical (ISM, 5.725–5.825) band.

Table 5: WINNER OFDMA parameters for Downlink [36].

Mode	TDD	FDD
Bandwidth	100 MHz	50 MHz
Carrier frequency	3.95 GHz 5 GHz (local area)	3.95 GHz
Frame length	0.6912 ms	0.6912 ms
OFDM symbols/frame	30	24
Subcarrier spacing	48.828 KHz	39.063 kHz
Cyclic prefix	1.2 μs	3.2 μs
No. used subcarriers	1840	1152
Signal bandwidth	90 MHz	45 MHz
No. subcarriers/chunk	8	8
No. symbols/chunk	120	96
No. chunks in DL/frame	230	2×144
Control and pilot symbols/chunks	16	16
Duplex guard time	0	8.4 μs

B. Pathloss-Equations for Wide Area Test Scenario

The path-loss equation [35] for the BS to MS link, assuming an urban macro-cell model (C2) with non-line-of-sight (NLOS), is given by

$$\begin{aligned} \mathrm{PL}_{\text{BS-MS}}\,[\mathrm{dB}] &= \left[44.9 - 6.55\log_{10}(h_{\mathrm{BS}})\right]\log_{10}(d) + 34.46 \\ &\quad + 5.83\log_{10}(h_{\mathrm{BS}}) + 23\log_{10}\left(\frac{f}{5.0}\right) + \sigma, \end{aligned} \tag{B.1}$$

where h_{BS} is the BS antenna height in meters, f the carrier frequency in GHz, d the transmitter-receiver separation in meters, and $\sigma = 8$ dB the standard deviation of the shadow fading. The link BS to RS is expected to be 3 dB better with respect to the link BS to MS due to some intelligence when selecting the RS location:

$$\mathrm{PL}_{\text{BS-RS}}\,[\mathrm{dB}] = \mathrm{PL}_{\text{BS-MS}} - 3. \tag{B.2}$$

For the interfering link from other BS, the path loss is obtained as in (B.1).

Alternatively, a more careful planning of the relay locations with line-of-sight (LOS) or obstructed LOS can be assumed. In that case the path-loss equation for the BS-RS link can be found from a stationary feeder model (B5f):

$$\mathrm{PL}_{\text{BS-RS}}\,[\mathrm{dB}] = 23.8\log_{10}(d) + 57.5 + 23\log_{10}\left(\frac{f}{5.0}\right) + \sigma, \tag{B.3}$$

where $\sigma = 8$ dB.

The path loss for the RS to MS link is based on an urban micro-cell model (B1) and can be found in LOS situations as

$$\begin{aligned} \mathrm{PL}_{\mathrm{LOS}}\,[\mathrm{dB}] &= \max\left\{22.7\log_{10}(d_1) + 41.0 + 20\log_{10}\left(\frac{f}{5.0}\right) + \sigma, \mathrm{PL}_{\mathrm{Free}}\right\}, \quad 30\,\mathrm{m} < d_1 < d_{\mathrm{BP}}, \\ d_{\mathrm{BP}} &= \frac{4(h_{\mathrm{RS}} - 1.0)(h_{\mathrm{MS}} - 1.0)f}{c}, \end{aligned} \tag{B.4}$$

where c denotes the speed of light and $\sigma = 3$ dB. For $h_{\mathrm{RS}} = 5$ m and $h_{\mathrm{MS}} = 1.5$ m, where h_{RS} and h_{MS} refer to the heights of RS and MS antennas, the breakpoint is at $d_{\mathrm{BP}} = 53$ m; $\mathrm{PL}_{\mathrm{Free}}$ is the path loss in free space. In NLOS situations the path loss can be found as

$$\begin{aligned} \mathrm{PL}_{\mathrm{NLOS}}\,[\mathrm{dB}] &= \mathrm{PL}_{\mathrm{LOS}}(d_1) + 20 - 12.5n_j + 10n_j\log_{10}(d_2) + \sigma, \\ n_j &= \max\{(2.8 - 0.0024d_1), 1.84\} \\ & 10\,\mathrm{m} < d_2 < 2\,\mathrm{km} \end{aligned} \tag{B.5}$$

with $\sigma = 4$ dB. We assume a geometry for d_1 and d_2, where the RS and MS are located in perpendicular streets. Furthermore, d_1 is the distance from the RS to the midpoint of the crossing and d_2 is the distance from the midpoint of the crossing to the MS whereas $d_1 = d_2$.

C. Pathloss-Equation for Metropolitan Area Scenario

A LOS link is assumed for nodes in the same street and a NLOS link for nodes in different streets and MSs are located inside of a building or in a street. The corresponding channel and path-loss models for all links are specified in [35]: urban micro-cell B1 LOS for nodes in the same street (B.4), urban micro-cell B1 NLOS for nodes in different streets (B.5), and the outdoor to indoor urban micro-cell model (B4).

The outdoor to indoor path-loss model consists of three components, the outdoor path-loss $\mathrm{PL}_{\mathrm{B1}}$ as defined by the urban micro-cell (B1 LOS/B1 NLOS) model, the penetration loss into the building PL_w, and the indoor path-loss PL_i. The path-loss equation is given as

$$\mathrm{PL}_{o2i}\,[\mathrm{dB}] = \min_n\{\mathrm{PL}_{n,\mathrm{B1}} + \mathrm{PL}_{n,w} + \mathrm{PL}_{n,i}\}, \quad n = 1,2,3,4, \tag{C.6}$$

where the path loss is calculated using the four points $n = 1, 2, 3$, and 4 of the outer walls of the building blocks that are closest to the indoor MS, and

$$\begin{aligned} \mathrm{PL}_{n,\mathrm{B1}}\,[\mathrm{dB}] &= \mathrm{PL}_{\mathrm{B1}}(d_{n,o}), \\ \mathrm{PL}_{n,w}\,[\mathrm{dB}] &= 13 + 15(1 - \cos\Theta_n)^2, \\ \mathrm{PL}_{n,i}\,[\mathrm{dB}] &= 0.5d_{n,i}. \end{aligned} \tag{C.7}$$

Moreover, $d_{n,o}$ denotes the distance to the closest point in all four streets surrounding the building block. Please note that $d_{n,o}$ is the distance traveled in the streets to reach these points and that the B1 path-loss model distinguishes whether the two nodes are in the same street or not, that is, line-of-sight (LOS) or NLOS path-loss model is used. Furthermore, Θ_n denotes the angle relative to the normal of the wall under which the signal is entering the building at the points closest to the MS, and $d_{n,i}$ denotes the distance to the MS inside the building block.

D. Pathloss-Equation for Local Area Scenario

A LOS or NLOS office propagation model (A1) [35] is employed depending on the presence of walls between the BS, RSs, and MSs. In particular LOS propagation model is used between BS and RS as well as between BS/RS and MS if there is a direct visibility. The LOS model is given by the following formula:

$$\mathrm{PL}_{\mathrm{LOS}}\,[\mathrm{dB}] = 18.7\log_{10}(d) + 46.8 + \sigma, \qquad \text{(D.8)}$$

where d denotes the distance in meters between the transmitter and the receiver and σ represents the standard deviation of the shadow fading and is equal to 3 dB. The NLOS propagation model is defined as

$$\mathrm{PL}_{\mathrm{NLOS}}\,[\mathrm{dB}] = 20.0\log_{10}(d) + 46.4 + 5n_w + \sigma, \qquad \text{(D.9)}$$

where n_w denotes the number of walls on a direct line between the transmitter and the receiver and $\sigma = 6$ dB. For the simulations light walls of the same type for all walls were assumed.

Acknowledgments

This work has been performed in the framework of the EU funded project IST-4-027756 WINNER II, which is partly funded by the European Union. The authors like to specifically acknowledge the contributing partners of the WINNER relaying task Daniel Schultz, Ralf Pabst, Niklas Johansson, Luca Coletti, and Mark Naden for their contribution to the development of the dynamic resource assignment framework and the cooperative relaying concept. Further, we would like to thank Carl Wijting and Kimmo Valkealahti for their contribution to the soft frequency reuse scheme and Elena Costa, Antonio Frediani, Ying Zhang, and Antonio Capone for their contribution to the dynamic resource sharing scheme.

References

[1] N. Esseling, B. Walke, and R. Pabst, *Fixed Relays for Next Generation Wireless Systems*, vol. 71–91, Springer Science+Buisness Media, New York, NY, USA, 5 edition, 2005.

[2] IEEE802.16, "TSGj -Mobile Multihop Relaying (MMR)," 2007.

[3] 3GPP, REV-080060, "Report of 3GPP TSG RAN IMT-Advanced Workshop," April 2008.

[4] "IST-Winner," http://www.ist-winner.org.

[5] ITU-R WP8F Document 8F/TEMP/1252-E, "Proposed new test environments and channel models of preliminary draft new report M.[Imt.Eval]," in *Proceedings of the 2nd Meeting of Working Party 8F*, Kyoto, Japan, May 2007.

[6] R. Pabst, D. Schultz, and B. Walke, "Performance evaluation of a relaybased 4G network deployment with combined SDMA/OFDMA and resource partitioning," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '08)*, Singapore, May 2008.

[7] V. Genc, S. Murphy, Y. Yu, and J. Murphy, "IEEE 802.16j relay-based wireless access networks: an overview," *IEEE Wireless Communications*, vol. 15, no. 5, pp. 56–63, 2008.

[8] I. -K. Fu, W. -H. Sheen, and F. -C. Ren, "Deployment and radio resource reuse in IEEE 802.16j multi-hop relay network in Manhattanlike environment," in *6th International Conference on Information, Communications and Signal Processing*, Singapore, December 2007.

[9] V. Genc, S. Murphy, and J. Murphy, "Performance analysis of transparent relays in 802.16j MMR networks," in *Proceedings of the 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, (WiOpt '08)*, pp. 273–281, Berlin, Germany, April 2008.

[10] W. Park and S. Bahk, "Resource management policies for fixed relays in cellular networks," December 2008, http://www.elsevier.com/locate/comcom.

[11] S. Lin, W. H. Sheen, I. Fu, and C. C. Huang, "Resource scheduling with directional antennas for multi-hop relay networks in Manhattanlike environment," IEEE Mobile Wimax Symposium, Orlando, Fla, USA, March 2007.

[12] S.-J. Lin, W.-H. Sheen, I.-K. Fu, and C.-C. Huang, *Resource Scheduling with Directional Antennas for Multi-Hop Relay Networks in a Manhattan-like Environment*, chapter 10, John Wiley & Sons, 2008.

[13] ETSI, "ETSI; recommendation TR 30.03 Selection procedure for the choice of radio transmission technologies of the UMTS," 1997.

[14] M. Kaneko and P. Popovski, "Radio resource allocation algorithm for relay-aided cellular OFDMA system," in *Proceedings of the IEEE International Conference on Communications*, pp. 4831–4836, Glasgow, Scotland, June 2007.

[15] T. Girici, "Joint power, subcarrier and subframe allocation in Multihop relay networks," *International Journal of Communication Systems*, vol. 22, no. 7, pp. 835–855, 2009.

[16] L. Huang, M. Rong, L. Wang, Y. Xue, and E. Schulz, "Resource scheduling for OFDMA/TDD based relay enhanced cellular networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '07)*, pp. 1546–1550, Hong Kong, March 2007.

[17] R. Pabst, D. C. Schultz, and B. H. Walke, "Combined uplink resource reservation and power control for relay-based OFDMA systems," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '08)*, pp. 2248–2252, Singapore, May 2008.

[18] E. Visotsky, Junjik B., R. Peterson, R. Berry, and M. L. Honig, "On the uplink capacity of an 802.16j system," in *IEEE Wireless Communications and Networking Conference (WCNC '08)*, pp. 2657–2662, Las Vegas, Nev, USA, 2008.

[19] H. Wu, C. Qiao, S. De, and O. Tonguz, "Integrated cellular and ad hoc relaying system: iCAR," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 2105–2115, 2001.

[20] Y.-D. Lin and Y.-C. Hsu, "Multihop cellular: a new architecture for wireless communications," in *Proceedings of the IEEE INFOCOM*, vol. 3, pp. 1273–1282, Tel Aviv, Israel, March 2000.

[21] H. Viswanathan and S. Mukherjee, "Performance of cellular networks with relays and centralized scheduling," *IEEE Transactions on Wireless Communications*, vol. 4, no. 5, pp. 2318–2328, 2005.

[22] C. Wijting, K. Doppler, K. Kalliojärvi, et al., "Key technologies for IMTAdvanced mobile communication systems," *IEEE Wireless Communications Magazine*.

[23] A. Frediani, S. Redana, E. Costa, A. Capone, and Y. Zhang, "Dynamic resource allocation in relay enhanced cells based on WINNER system," in *Proceedings of the16th IST Mobile and Wireless Communications Summit*, Budapest, Ungary, July 2007.

[24] S. Redana, L. Coletti, A. Capone, and L. Moretti, "A novel resource request and allocation strategy for relay based beyond 3G networks," in *Proceedings of the 8th World Wireless Congress*, pp. 95–100, San Francisco, Calif, USA, May 2007.

[25] K. Doppler, C. Wijting, and K. Valkealahti, "On the benefits of relays in a metropolitan area network," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '08)*, pp. 2301–2305, Singapore, May 2008.

[26] P. Rost, F. Boye, and G. Fettweis, "System performance analysis of single-path and cooperative MIMO relaying," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '08)*, Calgary, Canada, September 2008.

[27] M. Wódczak, "Cooperative relaying in an indoor environment," in *ICT Mobile Summit*, Stockholm, Sweden, June 2008.

[28] K. Doppler, C. Wijting, and K. Valkealahti, "Interference Aware Scheduling for Soft Frequency Reuse," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '09)*, Barcelona, Spain, April 2009.

[29] M. Werner, M. Naden, P. Moberg, et al., "Cost assessment and optimization methods for multi-node radio access networks," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '08)*, pp. 2601–2605, 2008.

[30] P. Moberg, P. Skillermark, N. Johansson, and A. Furuskär, "Performance and dost evaluation of fixed relay odes in future wide area cellular networks," in *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Athens, Greece, September 2007.

[31] B. Timus, "Cost analysis issues in a wireless multihop architecture with fixed relays," in *Proceedings of the IEEE Vehicular Technology Conference(VTC '05)*, vol. 61, pp. 3178–3182, Stockholm, Sweden, May 2005.

[32] K. Johansson, A. Furuskär, P. Karlsson, and J. Zander, "Relation between base station characteristics and cost structure in cellular systems," in *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC '04)*, vol. 4, pp. 2627–2631, Barcelona, Spain, September 2004.

[33] C. Wijting, K. Doppler, K. Kalliojärvi, et al., "WINNER II system concept: advanced radio technologies for future wireless systems," in *Proceedings of the ICT-Mobile Summit 2008*, Stockholm, Sweden, June 2008.

[34] M. Narandžic, C. Schneider, R. Thomä, T. Jämsä, P. Kyösti, and X. Zhao, "Comparison of SCM, SCME, and WINNER channel models," in *Proceedings of the IEEE Vehicular Technology Conference*, pp. 413–417, Dublin, Ireland, April 2007.

[35] WINNER II D1.1.2, "WINNER II channel models," September 2007, http://www.ist-winner.org/deliverables.html.

[36] WINNER II D6.13.14, "WINNER II System Concept Description," November 2007, http://www.ist-winner.org/deliverables.html.

[37] A. Osseiran, V. Stankovic, E. Jorswieck, T. Wild, M. Fuchs, and M. Olsson, "A MIMO framework for 4G systems: WINNER concept and results," in *Proceedings of the IEEE Workshop on Signal Processing Advances in Wireless Communications, (SPAWC '07)*, Helsinki, Finland, June 2007.

[38] E. Costa, A. Frediani, S. Redana, and Y. Zhang, "Dynamic resource allocation in relay enhanced cells," in *Proceedings of the 16th IST Mobile and Wireless Communications Summit*, Paris, France, April 2007.

[39] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[40] P. Herhold, E. Zimmermann, and G. Fettweis, "A simple cooperative extension to wireless relaying," in *Proceedings of the International Zurich Seminar on Digital Communications (IZS '04)*, pp. 36–39, Zurich, Switzerland, February 2004.

[41] P. Rost and G. Fettweis, "A cooperative relaying scheme without the need for modulation with increased spectral efficiency," in *Proceedings of the IEEE Vehicular Technology Conference(VTC '06)*, pp. 256–260, Montral, Canada, 2006.

[42] E. Zimmermann, P. Herhold, and G. Fettweis, "On the performance of cooperative diversity protocols in practical wireless systems," in *Proceedings of the 58th IEEE Vehicular Technology Conference(VTC '03)*, vol. 58, no. 4, pp. 2212–2216, Orlando, Fla, USA, 2003.

[43] E. Zimmermann, P. Herhold, and G. Fettweis, "On the performance of cooperative relaying protocols in wireless networks," *European Transactions on Telecommunications*, vol. 16, no. 1, pp. 5–16, 2005.

[44] E. Zimmermann, P. Herhold, and G. Fettweis, "Cooperative multi-hop transmission in wireless networks," *Computer Networks*, vol. 49, no. 3, pp. 299–324, 2005.

[45] M. Dohler, A. Gkelias, and H. Aghvami, "A resource allocation strategy for distributed MIMO multi-hop communication systems," *IEEE Communications Letters*, vol. 8, no. 2, pp. 99–101, 2004.

[46] M. K. Karakayali, G. J. Foschini, R. A. Valenzuelat, and R. D. Yates, "On the maximum common rate achievable in a coordinated network," in *IEEE International Conference on Communications*, vol. 9, pp. 4333–4338, 2006.

[47] M. H. M. Costa, "Writing on dirty paper," *IEEE Transactions on Information Theory*, vol. 29, no. 3, pp. 439–441, 1983.

[48] M. Wódczak, "Extended REACT—Routing information enhanced algorithm for cooperative transmission," in *Proceedings of the 16th IST Mobile and Wireless Communications Summit*, Budapest, Hungary, July 2007.

[49] P802.16j/D1, "Draft standard for local and metropolitan area networks–Part 16: air interface for fixed and mobile broadband wireless access systems–Multihop relay specification," August 2007.

[50] K. Brüeninghaus, D. Astely, T. Sälzer, et al., "Link performance models for system level simulations of broadband radio access systems," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC '05)*, vol. 4, pp. 2306–2311, Berlin, Germany, September 2005.

[51] Recommendation ITU-R M1645, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000," 2003.