Layer-2 Relays in Cellular Mobile Radio Networks

Bernhard H. Walke, Harianto Wijaya,
Daniel C. Schultz
Chair of Communication Networks (ComNets)
RWTH Aachen University, Faculty 6
Aachen, Germany
walke@comnets.rwth-aachen.de

***Abstract*— This paper discusses fixed layer-2 relays for infrastructure based radio network deployment concepts. Relay enhanced cells (RECs) for different optimizations goals like area size optimization, cell capacity optimizations in a given area and the application of relays to cover otherwise shadowed areas are introduced. As a basis for the proof of concept by means of simulation, a relaying capable MAC protocol as well as the used REC concept is briefly explained. The new REC concepts for both, area optimizations and capacity optimizations are validated by analytic and simulation results. Results are shown for the C/I in a multi-cellular environment and the throughput for an REC cluster with four relay nodes per REC using different cluster orders. The results are compared to that of a comparable single-hop cell cluster.**

Keywords- Fixed relays for cellular radio; multi-hop; Relay Enhanced Cells

I. INTRODUCTION

The range of radio interfaces like the one envisaged by 4G broadband systems as studied by the EU funded IST project WINNER [1] and IEEE 802.11/.16 based systems are limited by the high attenuation at carrier frequencies beyond 3.4 GHz, a limited transmission power (EIRP) owing to regulatory constraints and unfavourable radio propagation conditions, e.g., in densely populated areas. Conventional cellular radio network deployment concepts would require a very high density of base stations to achieve sufficient radio coverage there. As a consequence, the system deployment cost in terms of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for broadband radio will increase dramatically, resulting in a high cost per bit transmitted.

It is well known that an increased data rate (for a given power and carrier frequency) leads to a reduced radio range and that the available data rate decreases with increased distance from a base station (BS) as illustrated in Figure 1. In general, the service quality in terms of data rate, delay, outage probability, etc. seen by the user must not depend on its location in a cell.

Assuming a constant number of users per area element in a cell, the number of users increases linearly with the distance *d* from the BS. It appears reasonable that the requirements on 4G radio systems in terms of capacity, delay, user-experienced data rate and deployment cost cannot be met using conventional cellular deployment concepts. Instead, a novel disruptive deployment concept is urgently needed.

To meet the goal of low cost radio network deployment for both, short-range and ubiquitous (wide-area) coverage, fixed layer-2 relay node based deployment concepts appear to be the most promising technology. Relay nodes don't need a wired (fibre) backbone access reducing deployment costs (CAPEX and OPEX) and introduce a high flexibility in relay positioning, allowing a fast network rollout and adaptive traffic capacity engineering. Relays may also be used to provide indoor coverage from outdoor BSs.

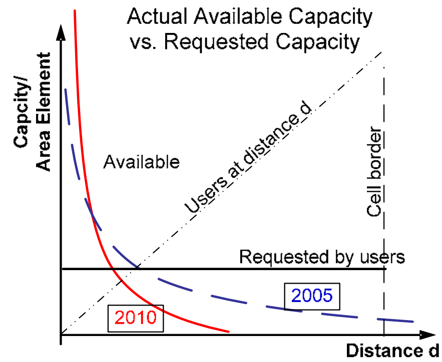

Figure 1. Facts in the available capacity vs. distance from a base station compared to the requested capacity

The proposed concept of using layer-2 relays as fixed infrastructure elements in an infrastructure based cellular deployment [4][9][10], differs from other concepts which assume the relays as mobile nodes, which randomly enhance a fixed infrastructure in an ad-hoc manner [7]. In the following they are being denoted Fixed Relay Nodes (FRN), although they could also be movable, i.e. temporarily fixed, in order to, e.g., temporarily increase the capacity in a certain service area, e.g. for the duration of an exhibition.

The different use cases of FRNs in infrastructure based deployment concepts are introduced in Section II. Section III and IV provide the basis for the performance analysis of RECs. Thereby Section III gives an example of a relay based cellular deployment, while section IV describes how relaying is performed based on an enhanced IEEE802.16 like (HiperLAN/2) MAC protocol. The performance of the presented multi-hop concept is shown by means of analytical and simulation results in Section V.

II. Relays in Infrastructure Based Deployment Concepts

A. *Relays to extend the service range of a BS (service area size optimisation)*

FRNs introduced to a cell (to become a Relay Enhanced Cell - REC) may be used to enlarge the coverage area of the BS as shown in Figure 2. If the FRN is placed outside the coverage area of the BS, antenna gain is needed to connect BS and FRN. The higher the antenna gain on the BS-FRN link the larger is the capacity available at the FRN. As the FRNs are placed outside the coverage area of the BS, the UTs connected to the FRNs are not able to listen to the BS, which means that all UT relevant information has to be forwarded by the FRN.

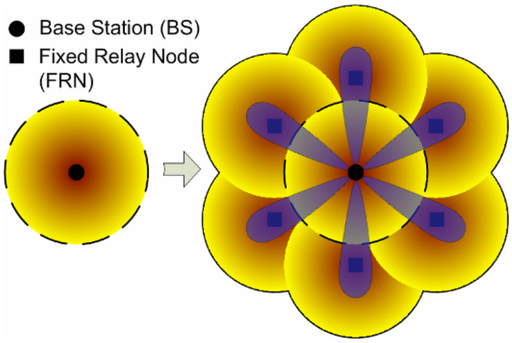

Figure 2. Left: Conventional cell; Right: Relay Enhanced Cell (REC) using layer-2 Relay Nodes (RN) to enlarge the cell area

B. *Optimised Cell Capacity and Minimum Transmit Power*

FRNs may be used in order to increase the capacity at outbound cell regions as shown in Figure 3. In both scenarios shown in Figure 2(right) and Figure 3(right) the capacity per area element in the REC approximates the requested capacity (see Figure 1) better than possible with a conventional (single-hop) cell. For a cellular radio deployment the channel re-use distance is minimised when receive antenna gain instead of transmit antenna gain is used.

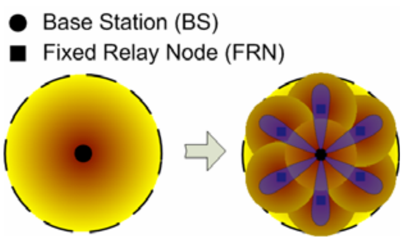

Figure 3. Left: Single BS cell; Right: REC with RN to increase the capacity at the cell border and balance the capacity per area element

The solution presented in Figure 3 can also be used to minimise the transmission power needed by user terminal (UT), BS and FRN. It is referred to as *Power Minimising* concept [7]. The power minimizing concept allows the UTs to benefit from the reduced energy consumption, whilst the reduced output power at BS and FRN leads to reduced hardware cost. Different from the area optimization concept as presented in subsection A, all UTs in the REC are able to listen to the BS, which can therefore broadcast control information to all UTs.

C. *Coverage of shadowed areas*

A capability not available from any other deployment concept is that a FRN can be used to serve areas otherwise shadowed from the BS as shown in Figure 4 [2][3].

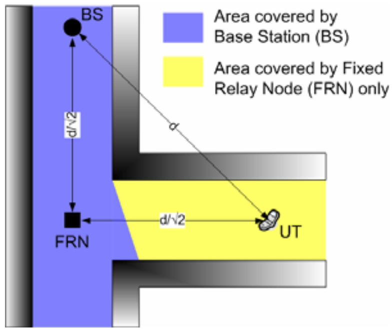

Figure 4. Relay Node to cover otherwise shadowed areas

III. Cell Planning With Relay Enhanced Cells

A transformation of a conventional single hop cell served by one BS solely to a relay enhanced cell (REC) served by one BS and 4 FRNs is shown exemplarily in Figure 5. In this case the REC aims for coverage extension and is area optimising.

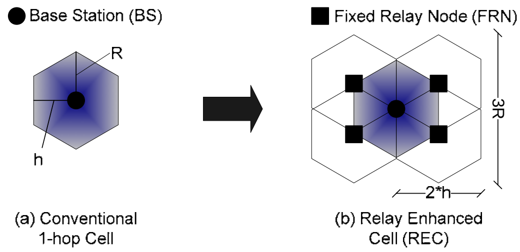

Figure 5. 1-Hop Cell (a) vs. Relay Enhanced Cell (REC) with 4 FRNs to increase the coverage area of the BS

Deploying the REC type shown in Figure 5 with the aim of capacity optimization, the distance between the FRN and BS is reduced from R= 200m to R'=100m resulting in a REC with the same shape but covering only ¼ of the area of the area optimized REC.

Like for conventional hexagonal single-hop cell deployments, RECs can be deployed in cell clusters, e.g., as shown in Figure 6. Due to the non circular symmetry three different re-use distances D1, D2 and D3 can be calculated in a REC cluster.

IV. Relaying Technologies

The relaying technology assumed is called Hierarchical Beacon with Fixed Slot Allocation (HBFSA) [5][6] that uses a frame based MAC protocol as found in IEEE 802.16 or HiperLAN/2.

Figure 7 shows the MAC frame of the HBFSA concept – that in this example is based on HiperLAN/2 - for a REC comprising one BS and two FRNs (A and B as shown in Figure 7). Both, the FRNs and the BS transmit their broadcast control channels (BCH, FCH and ACH) in each MAC frame. The payload (UL- and DL-Phase) of every 2nd MAC frame is

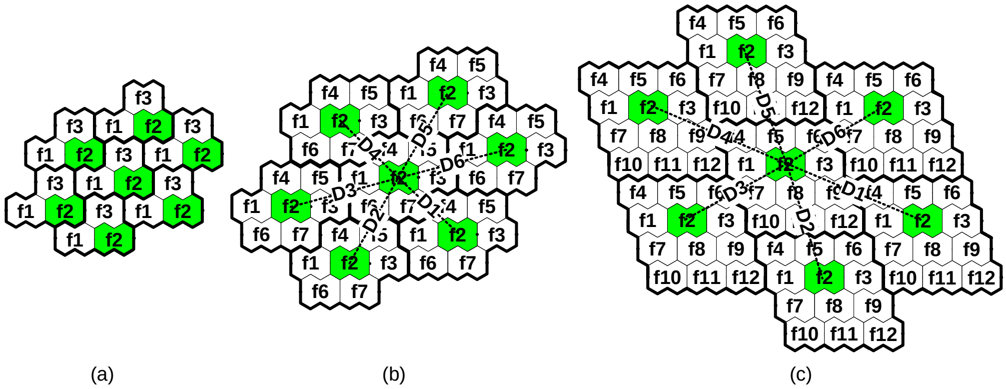

Figure 6. REC cluster for Cluster Orders CO=3 (a), 7 (b), 12 (c)

reserved for the BS exclusively. The BS has to use the payload to serve its UTs as well as to send and receive the multi-hop data traffic to and from the FRNs A and B. The remaining MAC frames are shared by FRN_A and FRN_B to serve their UTs.

Obviously, the overhead in the HBFSA concept increases with the number of FRNs served by one BS. In the HBFSA concept the FRNs are connected to the BS like a normal UT, whereby the BS has to adapt the structure of the MAC frame as shown in Figure 7. The FRNs appear to the UT like a BS.

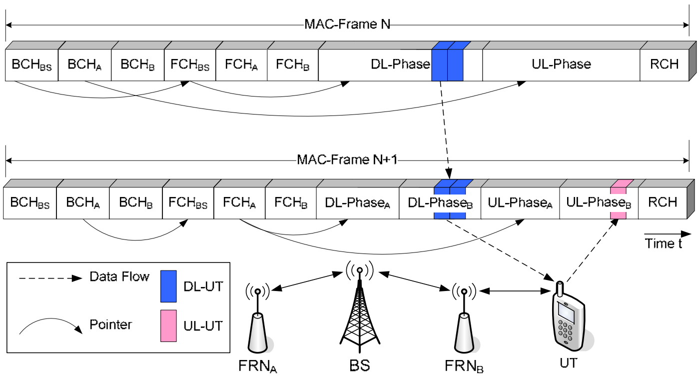

Figure 7: Relaying in time domain using the Hierarchical Beacon with Fixed Slot Allocation (HBFSA) MAC protocol

V. Results

In the following performance results for a cellular REC-based system with 4 FRN per cell (Figure 5 b) are presented that have been gained by mathematical analysis and by stochastic event-driven simulation studies for both concepts, area optimising (R=200m) and power minimising with cell radius R'=100m [11]. For the link between BS and FRN a receive antenna gain of 12dBi is assumed. Results for single-hop cells are presented as a reference, too.

The receive power P_R is calculated using a simple path loss model

$$P_R = P_S * G_S * G_R * \left(\frac{c_0}{4*\pi*f}\right) * \frac{1}{r^{\gamma}}; r > \left(\frac{c_0}{4*\pi*f}\right)$$

Input parameters are the send Power P_S, receive and send antenna gain (G_R and G_S), the speed of light c_0 and the used carrier frequency *f*. The path loss depends on the path length *r* and the path loss factor γ. For calculations and simulations an output power of 200mW (23dBm) is assumed. A channel bandwidth of 20 MHz in the 5GHz ISM band is assumed.

For all simulations and calculations it has been assumed that all UTs have line of sight (LOS) connection to the serving radio access point (RAP) that might be either a BS or FRN, so that they benefit from a low path loss factor of γ=2.0. For the inter-cell interference a path loss factor of γ=4.0 has been assumed that is typical in urban scenarios.

The simulation tool METEOR is proprietary and is based on SDL and C++ code, using the public domain ComNets Class Library (CNCL). The traffic load is assumed coming from Constant Bit Rate (CBR) sources.

A. *Single hop cell as reference*

The results depicted in Figure 8 (left) show that the mean C/I vs. distance from the BS depends on the Cluster Order (CO). A high CO value leads to better C/I values and thereby to a higher throughput, owing to a larger re-use distance. With an inter-cell path loss factor of γ = 4.0 a CO≥ 4 leads to a sufficient end-to-end throughput at the cell border as shown in Figure 8 (right), whilst a CO=3 is not sufficient.

B. *Results for an area optimised REC deployment*

Figure 9 shows the mean C/I (left) and the corresponding end-to-end throughput (right) achieved by an UT moving in X direction in the REC. The BS cell border shown serves as marker and should not be seen as the BS' signal coverage limit. The second marker on the right hand side points to the border of the REC at $D_{RECborder} = \sqrt{3} * R$. Due to the placement of the FRNs the C/I and the corresponding throughput reach a maximum at the BS cell border at $h = \sqrt{3}/2 * R$ where the UT has the shortest connection to the FRNs. Like in the single hop case the C/I and the respective throughput depend on the CO.

Comparing the results for the REC based deployment in an area optimised scenario against the 1-hop results it is visible that the range of the BS is dramatically increased in the REC based deployment concept. At a distance of 200m the REC shows for all COs an acceptable C/I. Also the C/I directly achieved close to the BS for CO=3 leads to a sufficient throughput on the first hop. The differences between the

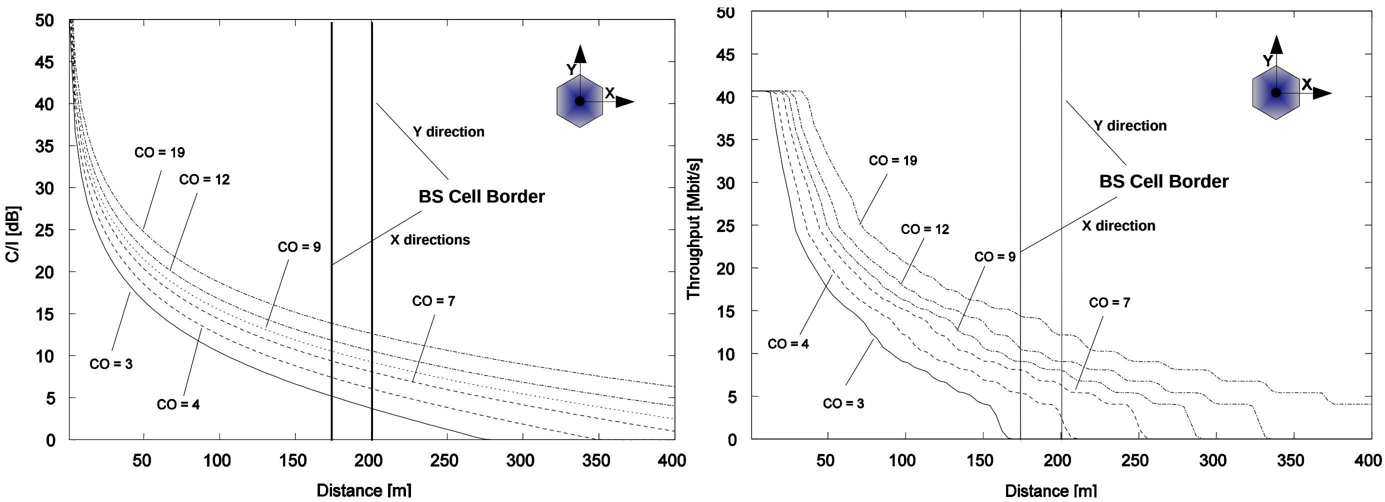

Figure 8: Results for a conventional (single-hop) cellular scenario with 200mW transmission power and γ = 4.0. Left: C/I; Right: Resulting throughput

conventional cell (Figure 8) and the one hop results in the REC can be explained by the increased re-use distance as a result of the larger cell sizes achieved by the placement of FRNs under the area optimising strategy.

Even at the border of the REC at a distance of 346 m the C/I is good enough to allow a throughput of around 5.2Mbit/s at CO=3 and around 7.5Mbit/s at CO = 12.

C. *Results for the power minimising REC deployment*

As explained in Section II relays can be deployed with the goal to minimise the output power of all devices, called power minimising concept. Figure 10 shows the results for an REC deployment with R'=100m resulting in a REC border at 176m in x direction. The transmission power is now reduced so that the SNR for the FRN-BS link is the same as in the area optimizing deployment. On the other hand the reduced power leads to reduced cell sizes and therewith to increased inter-cell interferences as shown in Figure 10. Thus only with a high CO the chosen power minimising strategy is able to serve the whole REC.

D. *Summary of results*

TABLE I. summarizes the values for the mean Throughput (T) and the resulting spectral efficiency (SE) for both, the 1-hop and the multi-hop cells assuming UTs equally distributed in the area.

For the area optimising REC deployment concept it can be seen that RECs provide less spectral efficiency than the respective 1-hop deployment caused by the much smaller cell sizes of the 1-hop cell deployment. But it has to be taken into account that for low CO (CO<7) no sufficient capacity is available at the cell borders in the single-hop scenario. Taking further into account that spectrum is a scarce resource and that the capacity of a single BS might not be consumed in its coverage area, an area optimized REC deployment with a low cluster order might be an attractive solution.

On the other hand, the power minimising REC deployment provides a higher SE compared to 1-hop cell clusters for CO≤7 due to the reduced output power and therewith reduced cell sizes. This results show that power minimising REC deployment concepts are beneficial for high load scenarios with high interference, e.g., densely populated areas.

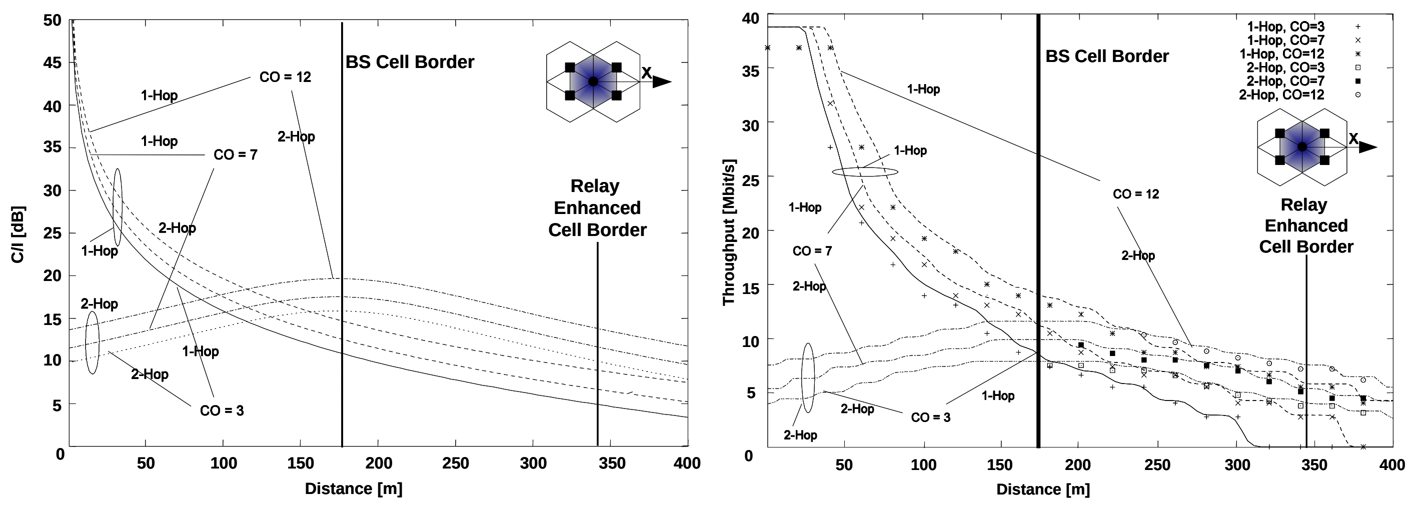

Figure 9. Results for a cellular system with 4 FRNs per REC, 200mW transmission power, γ =4.0 for inter-cell interference, γ =2.0 for the carrier signal, 12dBi antenna gain between BS and FRN, R=200m (Area Optimising) Left: C/I analytical. Right: Throughput in Mbit/s, analytical (lines) and simulation results (Markers)

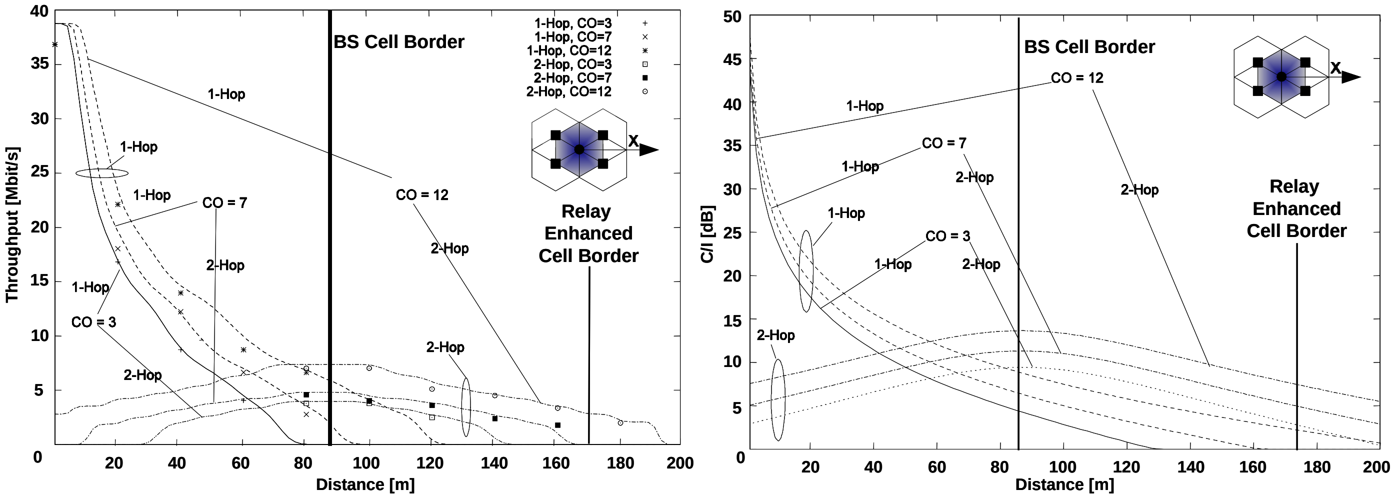

Figure 10. Results for a cellular system with 4 FRNs per REC, γ =4.0 for inter-cell interference, γ =2.0 for the carrier signal, 12dBi antenna gain between BS and FRN, R=R'=100m (Power Min.), 50mW transmission power, Left: C/I analytical. Right: Throughput in Mbit/s, analytical (lines) and simulation results (Markers)

TABLE I. MEAN THROUGHPUT (T) IN MBIT/S AND RESULTING SPECTRAL EFFICIENCIES (SE) IN MBPS/KM²/MHZ

	CO=3	CO=7	CO=12
T (single-hop)	6.15	9.61	12.66
T (REC- Area Opt.)	12.50	14.51	16.94
T (REC- Power Min.)	6.66	8.09	10.37
SE (single hop)	0,986	0,660	0,507
SE (REC- Area Opt)	0,601	0,299	0,204
SE (REC-Power Min.)	1.28	0.667	0.499

VI. CONCLUSIONS

This paper presents alternatives to apply relay enhanced cells using fixed layer-2 relay nodes in infrastructure-based cellular deployment concepts. Two optimisation strategies are considered, namely area optimisation and capacity optimisation. The benefits of relays to improve coverage to otherwise shadowed areas has been explained; quantitative gain results can be found in [2][3]. The analytical and simulation results prove the usefulness of relays for both, area coverage optimisation and capacity optimisation when using a MAC frame based system like IEEE802.16. The results prove the spectrum required for ubiquitous large area coverage can be reduced when using RECs as they can be deployed with low cluster order still providing sufficiently high throughput in the whole cell area.

The area optimising strategy, when applied with CO=1 and smart scheduling has the potential to reach higher SE than 1-hop, too.

The results for the capacity optimised (power minimised) REC deployment prove that RECs allow for higher spectral efficiency than available from conventional cell based systems. It has been shown that the capacity optimisation needs fine-tuning in sense of power adjustment vs. relay enhanced cell size, which might be scenario dependent.

ACKNOWLEDGEMENT

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