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Claudio Coletti[#1,], Preben Mogensen[#1,#2], Ralf Irmer[#3]

[#1] *Department of Electronic System,*
Radio Access Technology Section (RATE)
Aalborg University, Denmark
cco@es.aau.dk

[#2] *Nokia Siemens Networks,*
Research Center Aalborg,
Aalborg East, Denmark
preben.mogensen@nsn.com

[#3] *Vodafone Group*
Research & Development
Newbury, United Kingdom
Ralf.Irmer@vodafone.com

Abstract— **Relays are likely to play an important role in the deployment of Beyond 3G networks, such as LTE-Advanced, thanks to the possibility of effectively extending Macro network coverage and fulfilling the expected high data-rate requirements. Up until now, the relay technology potential and its cost-effectiveness have been widely investigated in the literature, considering mainly statistical deployment scenarios, like regular networks with uniform traffic distribution.**

This paper is envisaged to illustrate the performances of different relay technologies (In-Band/Out-band) in a realistic suburban network scenario with real Macro site positions, user density map and spectrum band availability. Based on a proposed heuristic deployment algorithm, results show that deploying In-band relays can significantly reduce the user outage if high backhaul link quality is ensured, whereas Out-band relaying and the usage of a lower frequency carrier at the Macro layer guarantee better network coverage and capacity improvements.

I. INTRODUCTION

Relays have been extensively studied as part of the Long Term Evolution-Advanced (LTE-A) study item [1]. Amongst the different benefits, Relay Nodes (RNs) are mainly expected to provide extended LTE coverage in targeted areas at a low deployment cost. Relaying for LTE has turned into a work item (WI) and is currently under standardization for 3GPP LTE Release 10. The overall objective of the WI is to specify Relays at least for coverage improvement purposes. Considering the different links shown in Fig. 1, it is possible to have the following configurations:

- The Macro eNodeB-to-relay link operates in the same carrier frequency as the relay-to-UE link (*In-Band Relaying*).

- The eNB-to-relay link operates in a different carrier frequency from the relay-to-UE link (*Out-Band Relaying*).

For each of the above configurations, the WI addressed the case where the eNB-to-relay link (*Backhaul link*) is operating in the same carrier frequency as eNB-to-UE link (*Direct Link*). Concerning the physical layer aspects specification, In-Band relaying operates for both downlink and uplink as follows: Backhaul and Relay Access links are time division multiplexed in a single carrier frequency (only one is active at any time) [1]. Furthermore, it had already been agreed in 3GPP that the Relay cells have their own Physical Cell ID (defined in LTE Rel-8),

and the relay node transmits its own synchronization channels and reference symbols. The UE shall also receive scheduling information and HARQ feedback directly from the relay node and send its control channels (SR/CQI/ACK) to the relay node. Therefore, the relay functionality added by this work item allows that all legacy LTE UEs can be served by the relay cells.
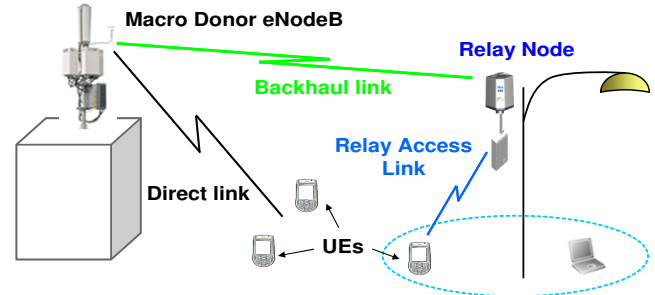

Figure 1: Overview of a Two-hop relay system and the different transmission links involved in a relay-enhanced network.

The performance of LTE Relaying (and Relaying for 802.16j [2]) has already been extensively studied [3][4] using statistical deployment scenarios. The 3GPP assumptions for relay evaluations are given in [5]. In [6] network coverage and capacity are studied for an area located in central London. The target of this paper is to provide further insight into the downlink performance of LTE relays for a realistic suburban deployment scenario. The city of Braunschweig, Germany, is used for our case study, with the existing 3G macro cell site locations of Vodafone-Germany used as the LTE macro site locations. Furthermore, we use the real Vodafone-Germany frequency Spectrum scenario for LTE deployment including both 800MHz and 2600MHz spectrum [7]. The remaining part of the paper is organized as follows: Section II provides the relay system model overview, Section III describes the simulation setup, Section IV illustrates the results of the performance analysis, and finally section V provides a conclusion.

II. RELAY SYSTEM MODEL

A. Relay Configurations and Resource Allocation Modelling

We consider a two-hop relay system in which three different types of links amongst the Macro Base Station (eNodeB), Relay Node and user equipment (UE) are defined as in Fig. 1.

The users can connect to either the eNodeB or Relay Node and they are denoted as Direct (or Macro) and Relay Users respectively. Moreover, two different Relay configurations, In-Band and Out-band, have been addressed in this paper, and Fig. 2 shows the resource allocation in both time and frequency domain for the different links involved in the relay transmission.
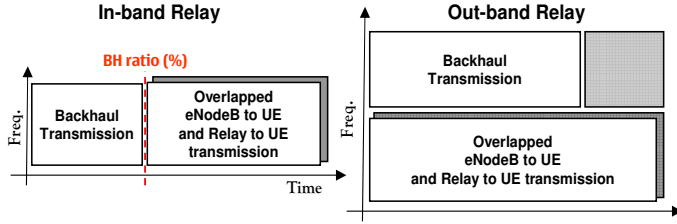

Figure 2: Relay resource allocation related to Half-Duplex In-Band Relaying and Full-Duplex Out-band Relaying.

With In-Band relay deployment, the same carrier is utilized for backhaul, access and direct transmissions, and relays are assumed to operate in a Half-Duplex fashion. In fact, Backhaul and Access transmission are split into two different time frames, and the percentage of time frames dedicated to backhaul is indicated with the term Backhaul ratio. In this study, the Backhaul link ratio is optimized on a cell basis in order to improve network coverage or, in other words, minimize the percentage of users that do not experience a predefined minimum required data rate (*User outage*). Regarding the downlink transmission towards UEs, direct and relay access transmissions are overlapped in both frequency and time domain, and interference amongst the different links is modeled. In case multiple relays are connected to the same Macro donor eNB, the backhaul link resources are shared among relay nodes, and each of them is assigned a resource share that is proportional to the number of users served in the access link.

Concerning Out-band relaying, backhaul and relay access links are orthogonal in the frequency domain, and we also assume that the two frequency carriers are sufficiently isolated so that backhaul and relay access transmission can happen simultaneously, i.e. in Full-Duplex mode. Further, the backhaul link can in general share resources with Macro users connected to the same carrier but in this specific study we assume the backhaul spectrum to be entirely dedicated to relay backhaul transmission and the Direct Users are served only by the Macro Cells operating also on the frequency of the relay access link.

With reference to the Direct and Relay Link, each type of base station has to distribute the available resources amongst the connected users, and a certain amount of resources is allocated to each user, depending on the user Signal-to-Interference-plus-Noise-Ratio (SINR). Each cell performs a resource allocation algorithm which is composed of the following two phases: in the first phase, the available resources are allocated in such a way that each user is ensured a predefined minimum required data rate. The resources are first allocated to the users with higher SINR as they require the least amount of resources to get the required data rate. If additional resources are available, these are assigned to each user in a round-robin fashion. In case the network load is very high or user SINR is extremely bad, resources may not be sufficient to meet the

minimum data-rate for each connected user and the worst-SINR users are likely to be in outage, i.e. their data rate is below the required one.

B. Proposed Relay deployment algorithm

The main goal of the proposed deployment algorithm is to deploy relays in the network such that the overall user outage is decreased. Such a coverage-oriented deployment approach is achieved by designing a specific metric for each potential relay location. If n relays have to be deployed in the network, the first n candidate positions that are sorted according to the related metric will be selected for deploying relays.

First of all, we consider a network area whose spatial resolution is denoted as pixel, and a certain percentage of the users are in outage. The set of relay candidate positions is then obtained by subdividing the entire map into small identical square regions so that a regular grid pattern is formed over the full investigated area, as illustrated in Fig. 3. The resolution of the grid gives the total number of candidate relay locations and it specifies also the number of pixels within each grid cell. Each candidate position is located at the center of a grid cell, and the metric related to i-th candidate location, $DFMetric_i$, is calculated as follows:

$$DFMetric_i = \sum_{l=1}^{\#pixels} \frac{NormTrafficDensity_l}{Throughput_{WB}(SINR_l)^n} \bullet \left(e^{t \cdot NormOutage_l}\right)$$

where for each pixel l lying in the i-th cell grid, the Normalized traffic density is proportional to user density, the wideband Throughput depends on the wideband SINR calculated in pixel l, and the $NormOutage_l$ stands for the normalized user outage relative to the Macro cell covering pixel l.
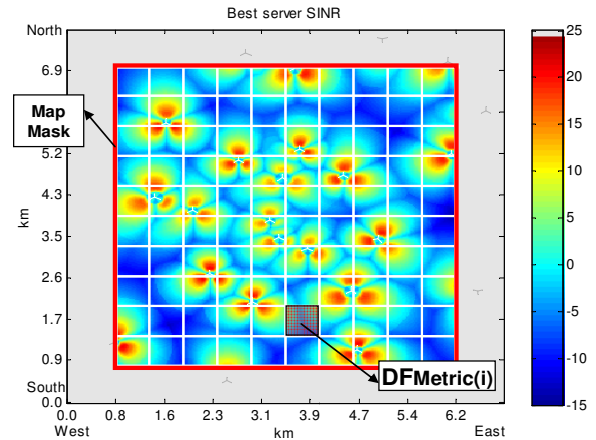
Figure 3: Overview of best server SINR map at 2.6 GHz with overlapping relay deployment algorithm grid pattern.

In order to properly balance the different terms in the formula, the exponential weights n and t are introduced. The former weights the impact of network Macro coverage over traffic density so that the low-SINR regions can significantly increase the overall metric; the latter is used to emphasize the relay locations where the overlaying Macro Cells have the highest number of users in outage. In order to extend network coverage and fully benefit from the relay multi-hop transmission, the

previously mentioned parameters allow for deploying relays at the cell-edge, with particular emphasis on those Macro cells where most of the users are not provided with the minimum data rate. Such a coverage-oriented approach will be pursued in this study. A minimum distance between two neighbor relays is considered to effectively spread the relays in the targeted areas based on relay transmission power and covered area.

III. SIMULATION SETUP

A. Network Layout

This study has been carried out for a suburban network scenario, shown in Fig. 3, which corresponds to an existing Vodafone 3G Macro Cellular deployment in Germany. The size of the investigated area is 7 km x 7.8 km containing 24 Macro sites with 3 Sectors. Each Macro site is considered upgraded to LTE with optimized antenna downtilt angles. In order to avoid border-effects, interfering cells from base stations located outside the examined area are taken into account. The resolution of the map, or pixel, has size 25 m x 25 m.

Fig. 4 shows the cumulative distribution function of Inter-Site Distance (ISD) between Macro sites. Considering only the closest site, the average ISD is approx. 1 km, and the ISD ranges between 400 m (downtown area) and up to 2 km (surrounding areas). A snapshot of network coverage (Best Server SINR) at 2.6 GHz is given in Fig. 3, and it can be noticed that the worst SINR regions, i.e. the "coverage holes", are located where the Macro site deployment is less dense. Moreover, the highlighted rectangular zone in Fig. 3 delimits the map mask, which is the area where the LTE users are randomly dropped according to user density information of the 2G and 3G network.
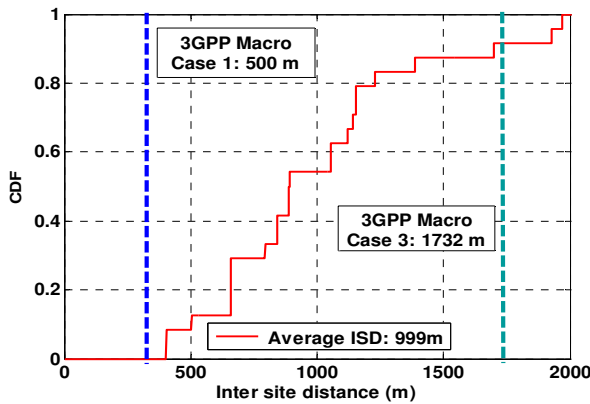

Figure 4: ISD CDF of the investigated scenario ftogether with 3GPP regular networks (Macro Case 1 and 3).

B. Simulation Setup and Simulation Cases Overview

The relay framework model, deployment algorithm, and network layout illustrated in the previous sections have been implemented in a Matlab-based network planning tool including a static network simulator. The main simulation parameters are listed in TABLE I. The performance indicators are obtained by means of a SINR-to-throughput mapping curve, which includes adaptive modulation and coding (AMC), HARQ and MIMO schemes up to 2x2 spatial multiplexing.

The SINR-to-throughput mapping curve is generated by extensive link-level simulations. 1200 active indoor users are considered in the full network area with minimum target data rate of 500 kbps; this minimum target data rate is also used to calculate user outage, which should be less than 5 %. With the above assumptions, the investigated LTE macro-eNodeB network is only able to provide an outage value of 10.7 % (or equivalent 89.3 % coverage). Therefore, relay deployment will be performed to reduce user outage to 5 %, according to the deployment algorithm described earlier.

TABLE I.   MAIN SIMULATION SETUP PARAMETERS

Cellular Layout	Realistic Braunschweig scenario
Path Loss model	Cost 231Hata for Direct and Backhaul link 3GPP model [5] for Relay access link
Traffic Model	Full Buffer, with 500 kbps as minimum required data rate.
Macro Tx Power	46 dBm per carrier
Macro Antenna Pattern	3D antenna pattern from [5] with realistic tilting angles obtained from network data
Relay Tx Power	37 dBm, with relays deployed outdoor
Relay Antenna Pattern	Directional antenna for Backhaul link (7dBi Gain, [5]) and Omni-antenna for access link.
User settings	1200 indoor users positioned according to Realistic user density map
Deployment algorithm parameters	Grid Square unit: 200 m x 200 m n = 0.5, t = 3 (coverage-oriented) Relay minimum ISD = 250 m.

In this study we apply frequency carriers and related bandwidths according to the German spectrum auction, as summarized in TABLE II. Regarding the spectra used to serve direct users, we can differentiate between Single-Band Macro, using the carrier at 2.6 GHz and Dual-Band Macro using also the lower spectrum band at 800 MHz. In case of Dual-Band Macro layer, the direct users can connect to only one of the two carriers, and the network load is split between the two bands based on the user SINR. Further, the Out-band Relay backhaul transmission takes place on a dedicated carrier in the 2.6 GHz spectrum in TDD mode, with half of the frames allocated to the downlink (and the other half for uplink).

TABLE II.   SIMULATION CASES AND SPECTRUM ALLOCATION OVERVIEW

Network Configuration	Spectrum Allocation		
	800 MH (FDD, 10 MHz)	*2.6 GHz (1) (FDD, 20 MHz)*	*2.6 GHz (2) (TDD, 20 MHz)*
Single-Band & In-Band Relay	-	Macro Direct Relay Access Backhaul	-
Dual-Band & In-Band Relay	Macro Direct	Macro Direct Relay Access Backhaul	-
Single-Band & Out-Band Relay	-	Macro Direct Relay Access	Backhaul only
Dual-Band & Out-Band Relay	Macro Direct	Macro Direct Relay Access	Backhaul only

IV. RESULTS AND ANALYSIS

In this section, the performances of Relays and Macro eNodeB-only deployments are presented, according to the simulation cases listed in TABLE II. User SINR, user outage

and user average throughput are the key performance indicators (KPIs) used to compare the different network configurations. A number of 50 outdoor Relays is considered for user SINR analysis, as this amount of Relays is sufficient to achieve, under certain assumptions, the 5 % user outage requirement.
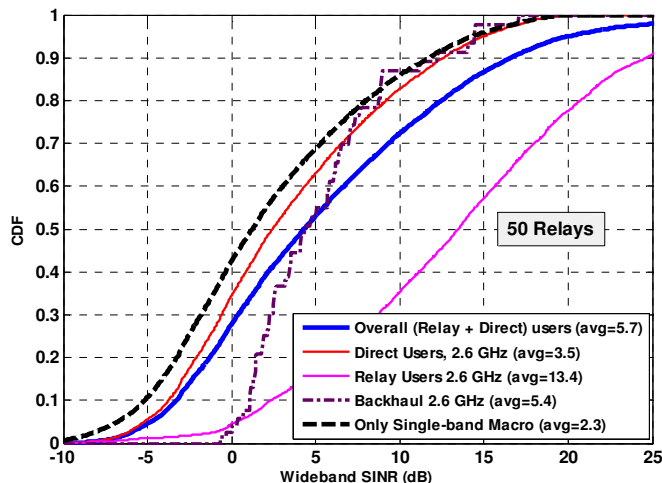

Figure 5: Wideband SINR distributions for Single-band Macro Scenario (dotted line) and In-Band Relay deployment (Direct, Relay and Overall user geometry, with Backhaul link geometry).

Fig. 5 shows the user wideband SINR distributions for both Macro-only and In-Band Relay deployments when a single carrier (2.6 GHz) is considered at the Macro Layer. By deploying 50 relays in the network, the average user SINR is improved by 4.6 dB compared to the initial Macro network without relays, thus extending network coverage. The relay users experience significantly high SINR values as the RNs are mainly deployed in coverage-limited zones and the selected minimum ISD amongst Relays guarantees low inter-relay interference. In addition to this, the direct users also experience better SINR because the users located at the cell-edge in the scenario with only Macro deployed are now served by relays, thus decreasing the distance between direct users and Macro server cells. The backhaul link outperforms the other links in the lower tail of the SINR distribution as a directive antenna at the relay side (7 dBi gain) enhances the backhaul link performances. Yet, the major limitation in the backhaul transmission is interference as the relays are deployed at the cell-edge and the utilized antenna gain is not sufficiently high to enhance the backhaul SINR. As a result, the backhaul link average SINR is dramatically lower than the one experienced by relay users.

As concerns user outage in the Single Band Scenario, the left graph in Fig. 6 illustrates the user outage sensitivity to the number of both In-Band and Out-band Relays. The single-band only Macro scenario gives a user outage of 10.7 %. With In-Band Relays, user outage turns out to be significantly sensitive to the number of relays if less than 50 In-band relays are deployed in the network. As the number of deployed relays increases, the user outage saturates, reaching 6 % outage with 100 deployed relays. The deployment of a large number of relays is unable to reduce the user outage to 5 % because the minimum ISD between relays is kept at 250 m, and relays are therefore spread all over the network. This also means that not every relay is deployed in those Macro cells that are affected

by the highest outage users. Secondly, the average in-band backhaul link SINR is not sufficiently high and thus the throughput of the in-band backhaul link limits the relay user outage performances. In addition to that, backhaul link resources also have to be shared amongst multiple relays, thus reducing the amount of backhaul link resources allocated to each single relay.
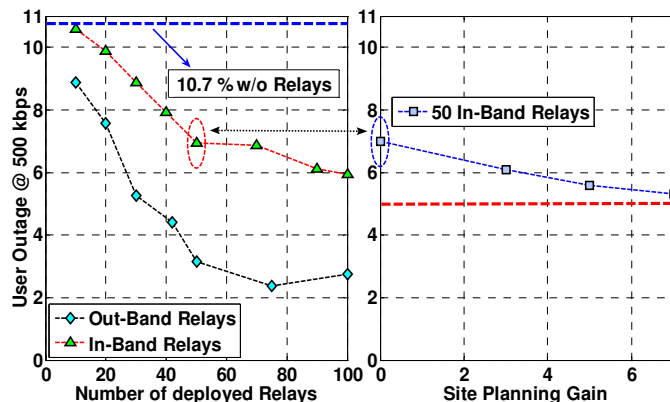

Figure 6: User Outage sensitivity to the number of deployed In-Band and Out-band relays and Site Planning gain applied to relay In-band backhaul link.

When Out-band relays are deployed, the use of a dedicated spectrum for backhaul transmission gives the best outage performances. On the 2.6 GHz TDD band, the backhaul link SINR is in the same order as for the In-Band relays case, as propagation and interference conditions do not significantly differ from the in-band backhaul transmission. The main difference comes from the fact that the backhaul link is provided with a larger amount of radio resources to be shared amongst the relays connected to the same donor Macro cell. For this reason, the Backhaul capacity is improved, and the number of relay users in outage decreases. With 50 Out-band relays, the outage level is far below the outage requirement (3.1 %); in fact, 30 out-band relays are sufficient to keep user outage in the proximity of 5%. Similarly to the In-Band Case, user outage reaches a plateau for more than 50 deployed relays for the same reasons as described earlier.

In order to evaluate the relay performance sensitivity to the backhaul link quality, we define the Site Planning gain as a gain to be applied to the backhaul link budget between the donor eNodeB and the relay. The rightmost graph in Fig. 6 shows that even with only 50 In-band relays the user outage can be reduced to approximately 5 %. This proves that the backhaul link quality is critical for In-Band relay deployment performances, and a Site Planning gain of 7 dB is necessary to reduce the outage to 5.3 %. In a real implementation, the site planning gain can be achieved by installing a more directive antenna at the relay side (14 dBi as overall antenna gain) or accurate positioning of relays so that Line-of-Sight (LOS) conditions are guaranteed for the relay backhaul link.

In Fig. 7, User wideband SINR distributions are shown for the Dual Band Macro layer case, considering both only-eNodeB and 50 In-Band relays. Similarly to the Single-Band Macro case, the deployment of 50 in-band relays yields gains in the overall user SINR distribution compared to the only-Macro scenario. It can be seen that the usage of the lower band

carrier at 800 MHz improves also the direct users' SINR since it provides better coverage, as compared to 2.6 GHz. The backhaul link SINR distribution is slightly improved compared to the Single-Band Macro case as the different outage level affects the deployment algorithm metrics and the selected relay positions.
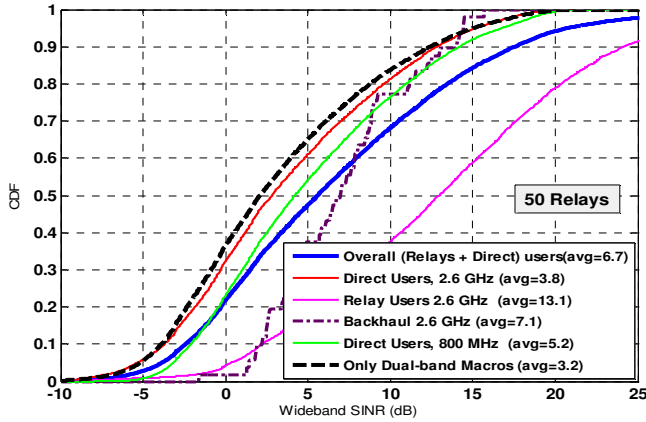

Figure 7: Wideband SINR distributions for Dual-band Macro Scenario (dotted line) and In-Band Relay deployment (Direct, Relay and Overall user geometry, with Backhaul link geometry).

Fig. 8 summarizes the outage values for a minimum target bit rate of 500 kbps and the different investigated network configurations. It can be observed that the deployment of only Dual-Band Macro sectors is sufficient to decrease the user outage to 3.8 % thanks to the added carrier at 800MHz and better propagation conditions. When In-Band relays are deployed on top of the Dual-Band Macro overlay layer, the user outage can be further reduced to 2.3 %, but the deployment of relays may not be needed as the Macro Layer is able to fulfill the outage level requirement on its own.
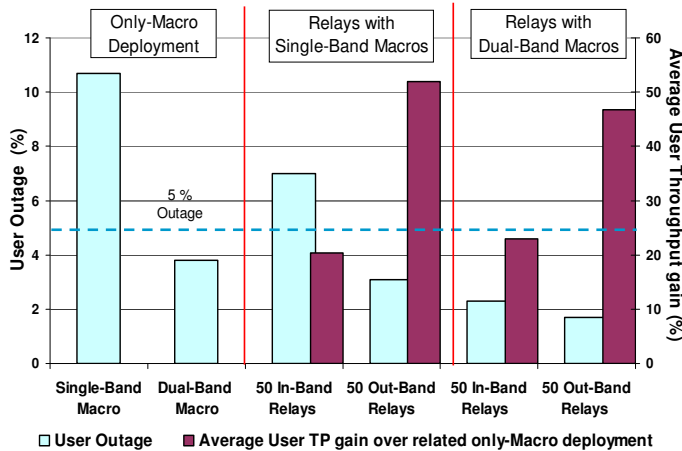

Figure 8: User Outage (left y-axis) and Average Throughput gains (right y-axis) for different network configurations without Relay Site planning gain.

Out-band relaying (using additional TDD spectrum for backhaul) reduces the user outage to 3.1 % and 1.7 % in Single-band and Dual-Band Macro Layer scenario respectively, even without any Site Planning gain applied to the Backhaul link. Furthermore, Out-band relaying outperforms In-band relaying also in terms of average user throughput, as illustrated

on the right-hand axis of Fig. 8. By considering both the Single-Band and Dual-Band only eNodeB scenarios as references, 50 In-Band and Out-Band relays give a gain of approximately 20 % and 50 % respectively over both the two only-eNodeB scenarios. Then it can be concluded that additional dedicated backhaul resources allow the out-band relays to yield a significant gain, not only in terms of user outage reduction, but also system capacity improvements. On the other hand, the dedicated backhaul band could of course also be used for access purposes.

V. CONCLUSIONS AND OUTLOOK

This paper analyzes the performance of downlink relaying for a realistic suburban area (Braunschweig, Germany) using a minimum user data rate of 500kbit/s as the main key performance indicator. With the existing macro site deployment, 10 % of the users are in outage and this is mostly due to lack of coverage. Relaying can potentially reduce the outage and it can be observed that the backhaul link quality is fundamental for the overall relaying performances. In our study we have mainly used low gain antennas (7dBi) at the relay node for the backhaul. With this assumption, even deploying a larger number of in-band relays does not give considerable improvements in user outage. High gain antennas at the relay for in-band backhaul link (larger than 14 dBi) are required to get substantial improvement from relay nodes. This, on the other hand, likely increases equipment and installation cost of relays, potentially making relays less attractive as a low-cost coverage solution.

The use of low frequency spectrum (10MHz at 800MHz) considerably decreases the user outage compared to only high frequency spectrum (20MHz at 2600MHz) in combination with a large number of relays. The obvious dilemma for in-band relaying is that the backhaul link in a time division manner is eating resources from access link. Hence Out-band relaying using dedicated spectrum for backhaul (not available for access link) provides significant improvements in user outage and average user throughput. In the study we used 20MHz of unpaired frequency band at 2.6 GHz, although one can debate if this assumption is realistic for a suburban area. Future works include urban deployment scenarios, where higher gains from Relaying are expected.

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