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Evaluation of Potential Relay Locations in a Urban Macro-Cell Scenario with Applicability to LTE-A

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***Abstract*— Relay base stations are expected to play an important role in extending coverage for beyond 3G networks, such as LTE-A. However, the signal quality experienced on the backhaul link between the macro-cell and the relay node has a major impact on the performance of the multi-hop transmission. This paper presents a measurement-based study focusing on the performance evaluation of the relay backhaul link for different potential relay locations and antenna configurations in a real urban macro-cell scenario. Based on the assumption that a similar network deployment would apply for LTE-A, a fully operational 3G network has been used for measuring both received signal strength and Signal-to-Interference-Ratio (SIR). Furthermore, the results have been used to estimate the performance of the multi-hop transmission under simplifying assumptions. The experimental results show that by increasing the relay height from 2.4 m to 5 m, the received signal strength improves on average by 1.7 dB for omnidirectional antennas. When a directional antenna is mounted at 5 m and pointed towards the serving macro cell, significant SIR gains (around 5.9 dB) and throughput improvements are achieved at the locations where the relay node and the macro-cell are in Line-of-Sight (LOS).**

I. Introduction

Relays have been extensively studied as a part of the 3rd Generation Partnership Project Long Term Evolution-Advanced (3GPP LTE-A) over the last few years [1]. In order to keep up with the always increasing data traffic demand, the deployment of relay base stations is envisioned to be an attractive feature for improving network coverage and also enhance user data rates [2–4]. As most of the available LTE spectrum will be released at higher frequency bands (e.g. the 2.6 GHz band), higher attenuation on the link between the user terminal and the serving macro-cell may result in network coverage issues. Therefore, increasing the density of the existing macro network with low-powered relay nodes is expected to boost the performance of cell-edge users with reasonable expenditure as compared to the major investments needed for deploying new macro site or acquiring lower frequency spectrum. Moreover, one of the limiting factors (and cost drivers) for small cell deployment is backhaul, since wired fiber access is in most cases cost-prohibitive or not feasible. From this perspective, relay wireless backhauling that uses LTE spectrum provides a competitive edge against wired backhaul although this comes with trade-off in capacity and shared radio resource usage.

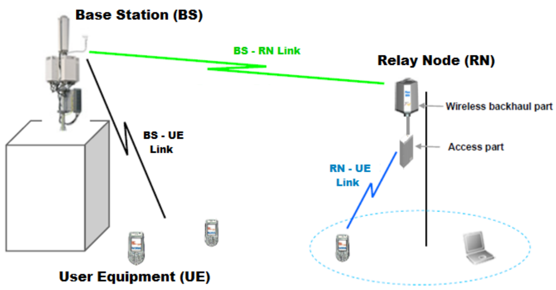

Fig. 1: Overview of the different transmission links involved in a relay-enhanced network.

By deploying relay nodes (RN), the distance between base station (BS) and user equipment (UE) is split into two hops, as shown in Fig. 1, thus reducing overall path loss between the UE and the BS. In a relay-enhanced network, there exist three different types of radio links: direct link (BS-UE), backhaul link (BS-RN) and access link (RN-UE). When considering the path loss associated with the previously mentioned links, the direct link between BS and UE is in general modeled with confidence thanks to previous extensive measurement-based investigations, e.g. [5], and the statistical models derived thereof. However, when the propagation occurs from over roof-top to street lamp post height, as illustrated in Fig. 2 for a typical backhaul link, the existing statistical models are less accurate [6]. Furthermore, some of the issues related to the backhaul link modeling are given by the use or assumption of planned relay node positions and/or directional characteristics of the link. Relay site planning is generally needed to boost the performance of the backhaul link so that it does not act as a bottleneck for relay access link transmission [3]. Because of this, a larger set of empirical data is required for extrapolating an accurate channel model for relay site planning.

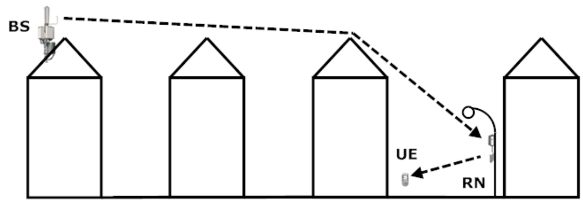

Fig. 2: Propagation mechanism in a urban relaying scenario.

This paper focuses on the performance of the backhaul link based on a measurement campaign conducted in a realistic urban scenario. A fully operational 3G network has been used for conducting the measurement campaign, and the main target is to show how sensitive relay deployment is with respect to receive antenna height, receive antenna type (omnidirectional or directional) and expected overall performance for different potential relay locations. Differently from [6] and [7], the results from the measurements include not only received signal strength but also the experienced Signal-to-Interference-Ratio (SIR), which describes the effect of interfering neighboring sites on the performance of the backhaul link. The measured SIR values are then utilized to estimate the achievable data-rates over the multi-hop transmission when different relay locations are considered. The remaining part of this paper is organized as follows: Section II describes the measurement campaign performed, Section III illustrates the results from the measurement campaign results, Section IV gives an overview of the achievable relay performance, and finally, Section V provides a conclusion.

II. Measurement Campaign

The measurement campaign was performed in the city centre of Aalborg, Denmark. The environment, illustrated in Fig. 3 is a typical urban medium city where average building height and street width are about 15-18 m (3-4 floors) and 7-12 m, respectively. Measurements were made on the 2100 MHz High-Speed Downlink Packet Access (HSDPA), Wideband Code Division Multiple Access (WCDMA) network of the telecommunications operator Telenor.

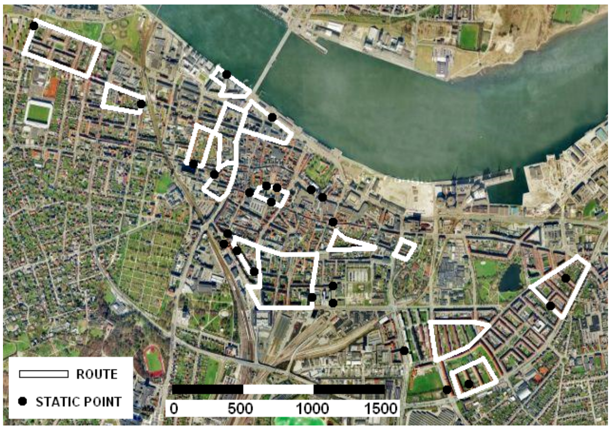

Fig. 3: Aerial view of the measurement area.

For this area, base stations are normally located above roof-top. 15 different nodes (45 cells) placed around the city centre were included in the campaign. The average inter-site distance is approximately 600 m. Transmit antennas are typical sectorial with 65° half-power beamwidth in azimuth and 5° in elevation, and a maximum gain of 18 dBi. The maximum transmitted power is set at 43 dBm.

At the reception end, two different types of antennas were used: two omnidirectional dipole antennas, with a gain of 2 dBi, were mounted on a van to perform drive measurements at 2.4 m and 5.0 m height. In addition to this, a directional antenna, with 8 dBi of gain and a beamwidth of 80° in azimuth and 60° in elevation, was mounted on a 5 m high mast in order to simulate a lamppost relay and perform static measurements. The whole measurement setup is illustrated in Fig. 4.

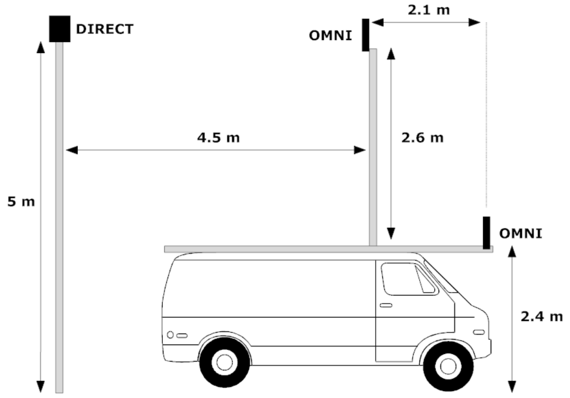

Fig. 4: Measurement setup with 3 different receive antennas.

The drive measurements consisted in driving the 15 different routes indicated in Fig. 3 across the city. These routes were located at cell-edge and included different kinds of propagation scenarios such as In-between-Building (IN-BB) or Line-of-Sight (LOS). The objective was to evaluate height gain, so the highest power signal from the different base stations was recorded at these two different heights (2.4 m and 5.0 m). The average length of the routes was 750 m, the average speed was 14 km/h and the sampling speed was 20 samples/s; effectively, there were 3857 samples available for comparison on each of the routes.

The static measurements were performed at the 25 different locations shown in Fig. 3. The positions were selected on a qualitative basis to include different, and what was deemed typical, relay positions for a lamp post mounted relay. In this sense, the chosen positions reflect the practical situation, where performance optimized planning is usually not possible. The directional antenna was pointed in the direct LOS direction towards the base station (sector) with the highest average signal level in the area - named hereafter "the donor base station". According to propagation conditions, the measured positions can be classified as follows:

- LOS: direct view of the donor base station (clear LOS) or directional antenna pointing to a main street directly illuminated by the donor base station (almost LOS).
- IN-BB: typical In-between-Building locations or environments where it is possible to point the directional antenna along a street towards the desired donor base station. This is the most probable location for relay deployment (typical pedestrian street, commercial areas, etc.). An example of this scenario can be seen in Fig. 5.
- OTHER: Non-Line-of-Sight (NLOS) or severely shadowed environments (very narrow streets between tall buildings) where the link between the directional antenna and the desired donor base station is obstructed.

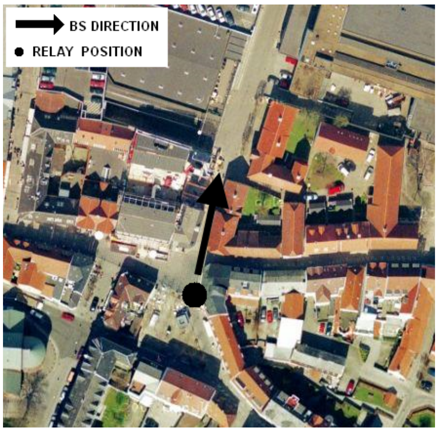

Fig. 5: Potential location for relay deployment in a pedestrian street inside a commercial area.

III. Analysis and Discussion of Measurement Results

Measurements focused on Received Signal Code Power (RSCP) and Interference Signal Code Power (ISCP). From these two parameters, Signal-to-Interference-Ratio (SIR) is defined in WCDMA as indicated in Eq. (1) with a spreading factor (SF) equal to 256 [8].

$$SIR = RSCP - ISCP + 10 \cdot log_{10}(SF) \quad (1)$$

Results are presented and analyzed for the drive measurements in the first place (omnidirectional antennas at different heights), and then for the static measurements (directional antenna and omnidirectional antenna at same height). Although the values are extracted from a 3G network, the conclusions drawn from the measurements would be applied to an LTE-A system. RSCP ans ISCP are averaged over a 5 MHz bandwidth, but the differences in signal strength between two different antenna configurations are representative also for larger bandwidths, such as 20 MHz for LTE-A. Then, the measured SIR can be used to estimate the corresponding wideband SIR for an LTE-A system, as explained in Section IV.

A. Height gain with omnidirectional antennas.

To evaluate the effect of the receive antenna height, the measurements from the omnidirectional antenna at 5.0 m were compared sample by sample with the measurements from the omnidirectional antenna at 2.4 m. This comparison was done in terms of received power (RSCP) and SIR as indicated in Eq. (2) and Eq. (3).

$$RSCP\text{-}HG = RSCP_{\ OMNI\ 5m} - RSCP_{\ OMNI\ 2.4m} \quad (2)$$

$$SIR\text{-}HG = SIR_{\ OMNI\ 5m} - SIR_{\ OMNI\ 2.4m} \quad (3)$$

where RSCP-HG (RSCP Height Gain) and SIR-HG (SIR Height Gain) indicate the gain in signal level or SIR at 5.0 m compared with the signal level or SIR at 2.4 m, respectively.

Fig. 6 shows the average RSCP-HG for each route. Received power is on average 1.77 dB higher at 5.0 m than at 2.4 m. These power height gain results are in agreement with [6] and [7]. Received power increases with height, or in other words, link path loss decreases with increased receive antenna height. For some routes, this value is around 3 dB which is the typical floor height gain considered in many studies [9].

The irregular result observed in Route 15 is explained by the complex propagation condition at some points of the route, where the classification condition was not always IN-BB as in the other cases.

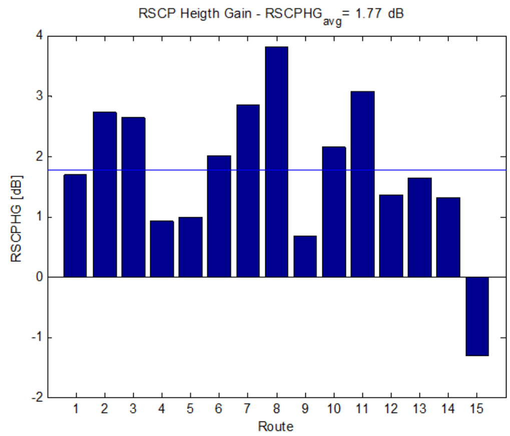

Fig. 6: RSCP Height Gain

The average SIR-HG for each route can be seen in Fig. 7. The measured SIR is on average 1.83 dB lower at 5.0 m than at 2.4 m. This means, that received power is higher at 5.0 m, but also interference from other base stations, which leads to a lower SIR.

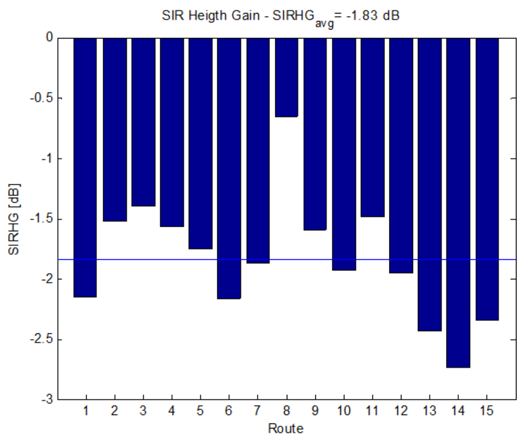

Fig. 7: SIR Height Gain

B. Directional antenna vs. omnidirectional antenna.

The impact of different antenna types was investigated on the static positions. In this case, the measurements from the directional antenna at 5.0 m are compared with the measurements from the omnidirectional antenna at same height as previously explained.

This comparison is done as in the previous section, in terms of RSCP and SIR as indicated in Eq. (4) and Eq. (5).

$$RSCP\text{-}TG = RSCP_{\ DIRECT\ 5m} - RSCP_{\ OMNI\ 5m} \quad (4)$$

$$SIR\text{-}TG = SIR_{\ DIRECT\ 5m} - SIR_{\ OMNI\ 5m} \quad (5)$$

where RSCP-TG (RSCP Type Gain) and SIR-TG (SIR Type Gain) indicate the gain in signal level and SIR from the directional antenna at 5.0 m compared with the signal level and the SIR from the omnidirectional antenna at the same height, respectively.

The different patterns have an impact in both RSCP and SIR, but more highlighted in SIR, since the directional antenna is expected to be capable of filtering interference with respect to the omnidirectional antenna.

Fig. 8 shows RSCP-TG for the 25 different positions measured. It can be seen that in both LOS and IN-BB situations, RSCP-TG is larger than 0 dB, which means that received power level is higher for the directional antenna than for the omnidirectional antenna. For the considered static positions, RSCP-TG is on average 6.33 dB for LOS and 3.70 dB for IN-BB. This difference can be explained by the fact that multi-path is more pronounced in IN-BB locations and thus means that despite of the lower gain of the omnidirectional antenna, it is capable of collecting more power from different reflections. This behavior is even more marked in the OTHER locations where RSCP-TG is smaller than 0 dB.

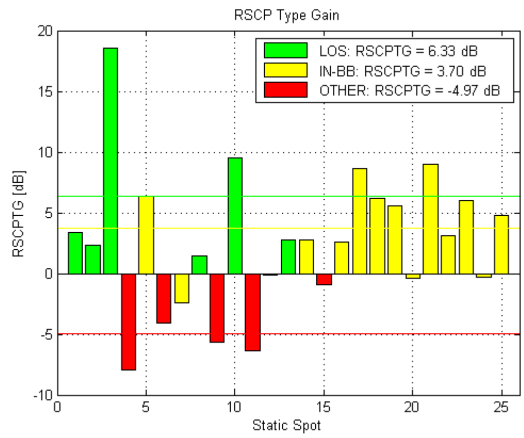

Fig. 8: RSCP Type Gain

Fig. 9 illustrates SIR-TG for all the different measured locations. For the locations where SIR-TG is larger than 0 dB, it can be concluded that the directional antenna is capable of filtering interference compared to the omnidirectional located at the same position. SIR-TG is on average 5.82 dB for LOS and 1.73 dB for IN-BB. This means that it is possible to filter more interference when pointing directly to the desired donor base station in LOS conditions than in typical IN-BB situations where relays are expected to be deployed.

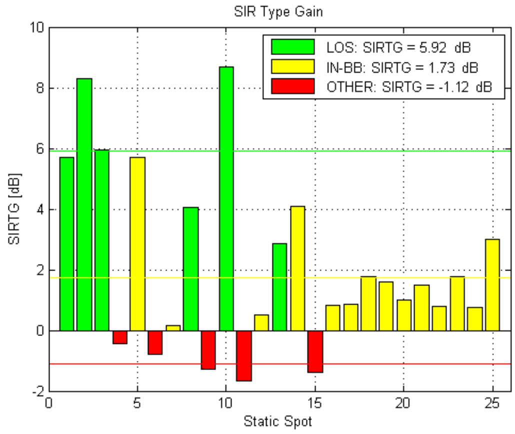

Fig. 9: SIR Type Gain

As it can be seen for OTHER locations, the directional antenna presents a lower SIR than the omnidirectional, indicating that the directional antenna is incapable of filtering interference in environments that are highly affected by shadowing.

Focusing on the IN-BB locations, the directional antenna does not give a significant gain in terms of SIR compared with the omnidirectional. In some cases, the problem comes when deciding where to point the directional antenna since the direction to the desired donor base station can be blocked by a building. This means, that more accurate positioning of the relay node is needed so that a clear desired signal from the selected donor can be received (i.e. pointing the directional antenna along a street towards the donor base station).

IV. RELAY PERFORMANCE EVALUATION

To analyze the benefits of using a RN instead of a conventional direct link (BS-UE), a study has been carried out based on the previous measurements assuming that the observed statistics and scenario would apply to an LTE-A deployment of relay nodes. One LOS and four IN-BB locations have been selected to compare the actual performance of the direct link from a BS to a UE placed at 2.4 m height with a relayed link (BS-RN-UE) where the RN uses a receive directional antenna placed at 5.0 m. At each of the potential RN locations, the lowest 5%-ile SIR on the direct link from UEs located in the dominance area of the RN is selected, assuming a maximum radius of 44 m for the relay cell. Then, the performance on the direct link will be compared with the relayed link. The SIR values on the different links are shown in Table I.

A. *Performance modelling.*

In order to consider the wideband SIR (SIR_{wb}) values that are experienced on the traffic channel of an LTE-A transmission in the downlink, the measured SIR must be corrected by considering the spreading factor on the HSDPA traffic channel ($SF = 16$) in Eq. (1). Moreover, considering also that the RSCP is calculated on the pilot bits while the ISCP is calculated considering orthogonal and non-orthogonal parts, it is necessary to re-scale the overall power which can be received on the traffic channel by a factor of approximately 10. The resulting SIR_{wb} can be mapped into throughput (TP) using a simple model based on a modified Shannon capacity formula [10] such as indicated in Eq. (6).

$$TP = 0.18 \cdot M \cdot \beta \cdot min\left\{10.5\ ,\ log_2\left(1 + \frac{10^{\frac{SIR_{wb}}{10}}}{\mu}\right)\right\} \quad (6)$$

where $M = 100$ is the number of physical resource blocks occupied in a 20 MHz LTE-A transmission, and $\beta = 0.64$ and $\mu = 1.67$ parameters for the mapping in a macro scenario.

The overall throughput for the different links is indicated in Eq. (7) for the direct link and in Eq. (8) for the relayed link.

$$TP_{direct} = TP_{BS-UE} \quad (7)$$

$$TP_{relayed} = min\left(TP_{BS-RN}, TP_{RN-UE}\right) \quad (8)$$

Assuming that the UE is in close proximity of the RN, i.e. LOS conditions and significantly high SIR compared to other links, the performance over the complete relayed link is limited by the throughput experienced in the backhaul link as specified in Eq. (9). From this value, it is possible to calculate the effective throughput (TP_{eff}) by supposing half-duplex mode of operation. As realistic traffic load is not considered at the donor base station in terms of connected UE or multiple relays, a 50:50 time split between backhaul and access transmission subframes is assumed to calculate the end-to-end throughput. In this case, $TP_{eff,relayed}$ is half of $TP_{relayed}$ as indicated in Eq. (10).

$$TP_{relayed} \approx TP_{BS-RN} \quad (9)$$

$$TP_{eff,relayed} = {}^1\!/_2 \cdot TP_{relayed} \quad (10)$$

To compare the performance over the two different end-to-end links, two metrics are defined: SIR gain (ΔSIR) and throughput gain (ΔTP).

TABLE I: Estimated SIR and throughput gains by using a relay at different potential locations.

$\mathbf{SIR_{BS-UE}}$ [dB] $\mathbf{UE: 2.4\ m, 5\%}$-ile	Relay Type	$\mathbf{SIR_{BS-RN}}$ [dB] $\mathbf{RN: 5.0\ m}$	**ΔSIR** [dB]	**ΔTP** [%]
3.50	LOS	15.00	11.50	109
10.40	IN-BB	16.57	6.17	-11
5.60	IN-BB	14.59	8.99	44
4.30	IN-BB	10.11	5.8	13
2.10	IN-BB	7.61	5.51	21

B. *Performance evaluation results.*

The different SIR gain values shown in Table I are according to the type of location. In LOS, the highest gain is achieved (11.5 dB). In the IN-BB situations studied, this gain is lower and varies depending on the location. The average value of this gain in IN-BB conditions is 6.61 dB. As expected, the LOS relay, with the highest SIR gain leads to the highest throughput gain (109%). For this potential location, the RN can double the throughput experienced by a UE connected to it. One of the IN-BB potential locations presents a negative throughput gain (-11%), which means that for that particular location, SIR on the backhaul link is not sufficient to achieve a gain from relay deployment. For the other IN-BB locations, the average throughput gain is 26%, which is more than 3 times smaller than the one experienced in the LOS case.

V. Conclusion

This study analyzed the performance of the wireless backhaul link in an LTE-A relaying scenario by investigating the impact of the receive antenna at different potential relay locations. The performance evaluation has been based on measurements made in a real urban 3G macro-cell radio network, with relay positions chosen for typical LTE-A extension of the network. The analysis results show that both relay antenna height and type have an impact on the base station to relay link. Received power increases with height, with an average gain of 1.7 dB by increasing antenna height from 2.4 m to 5 m. The use of a directional antenna allows for filtering interference, obtaining an average SIR gain of 5.9 dB in LOS and 1.8 dB in in-between building locations compared to the omnidirectional antenna. By increasing SIR using directional antennas, the overall throughput experienced by a user connected to the relay is improved. It can be concluded that LOS conditions are required to enhance the cell-edge performance of relayed networks. If relays cannot be deployed in LOS conditions, more accurate positioning of the relay backhaul antenna has to be performed (i.e. increased antenna height), which would also affect the deployment costs.

Acknowledgment

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