LTE-Advanced Relaying for Outdoor Range Extension

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***Abstract*—Future cellular wireless networks based on MIMO-OFDM enable high data rates in outdoor scenarios. Limitations in coverage, especially at cell-edge, might be overcome by transmission over relays, which is therefore widely discussed for LTE-Advanced networks. Here, a multi-hop relay node is placed at the cell-edge or in a coverage hole in order to compensate for the penetration path loss caused by buildings. Relay nodes can be deployed in two modes, either as amplify and forward or as decode and forward relay. The later system may benefit from independent link adaptation which is a key concept especially under fading conditions in outdoor broadband wireless. This paper reports on first multi-hop relaying field trials in the LTE downlink. These field trials were carried out in a single-cell, single sector urban outdoor environment within the Berlin LTE-Advanced Testbed. Results show that outdoor relaying is a key concept to deliver high data rates to the cell edge. Furthermore, results show that rates above 60 Mbps are achievable and outdoor relaying yields for a 300 m range extension. In addition, results show that multi-hop relaying provides cell-edge users with a minimum data rate of at least 20 Mbps which is mandatory, especially if QoS constraints have to be met.**

I. Introduction

3G Long Term Evolution (LTE) technology utilizes MIMO-OFDM concepts to deliver high data rate over small cells. The limitation of cell size is mainly caused by increasing path loss attenuation at a high carrier frequency of 2.6 GHz. In addition, a high degree of base station downtilting angle [1] is presently considered to limit cell size and reduce interference in neighboring cells. Such a deployment scenario further limits the range extension capability with LTE technology in terms of coverage and capacity. Coverage holes caused by low receive signal power are usually a result of non line of sight (NLOS) reception due to building penetration loss. LTE key concepts like frequency dependent link adaptation and cross-polarization multiplexing cannot overcome this low peak power constraint. One of the study items of LTE-Advanced (LTE-A)/ IMT-Advanced (IMT-A) [2] is therefore to improve coverage in existing LTE networks by deploying full decode and forward relays. Outdoor and indoor deployment concepts have been proposed in [3]. In-depth system level analysis has been performed in the European WINNER project [4] where it was shown that relaying improves link efficiency by 45% if deployed in single-site SFN mode.

To complement results obtained in these studies with real measurement data, we implemented a relaying testbed enabling transceiver concepts such as half-duplex interference suppression, self-synchronization and IP forwarding. This relaying prototype is an evolution of the LTE testbed used for the first multi-user LTE downlink field trials conducted by Heinrich Hertz Institute (HHI) and Nokia Siemens Networks (NSN) in Berlin in October 2007 [5], [6]. The testbed incorporates LTE key features such as frequency dependent scheduling in 20 MHz bandwidth, adaptive MIMO mode selection for 2x2 MIMO utilizing spatial multiplexing [7], and low round-trip delay on the PHY layer of 8 ms. By field trial measurements using this LTE relay node (RN), we demonstrate that relaying has high impact on coverage and capacity expectations.

II. System design and implementation

A. Relaying concept

The relaying concept is shown in **Fig. 1**. Here, relaying is explicitly shown for the downlink, but can be used in the uplink just vice versa. The relay node (RN) or user equipment (UE) is connected via direct link to the base station (BS) in the 1st hop where the BS transmits with transmit power p_1. To increase capacity in areas with poor channel conditions, especially at the cell edge or in a coverage hole, the UE can perform a handover and connect via RN to the BS in a 2nd hop. The relay node (RN) is fixed and placed in a way that it experiences high received signal power from the BS, e.g. in the line of sight (LOS) path to the BS. The RN transmits with a much lower transmit power $p_2 \ll p_1$. Since the distance and therefore the path loss between RN and associated UE is much smaller than the path loss in the direct link, the capacity for the cell-edge UE is increased.

The basic LTE testbed operates in FDD mode, decoupling up- and downlink in the frequency domain. In the LTE relaying testbed, first and second hops are separated in time domain using a flexible duty cycle ratio which is adjustable to 4/6, 5/5 or 6/4 over 10 subframes and form one radioframe of 10 ms. The timing diagram used in the implemented LTE RN is shown in **Fig. 2**. The entire frame structure can be divided into two types of time slots: direct transmission time slots and relaying time slots. Users with a good connection to the serving BS are admitted to the direct transmission time slots. Users with a weak connection to the BS identify a nearby relay node and are admitted to the relaying time slots. Remark: This half

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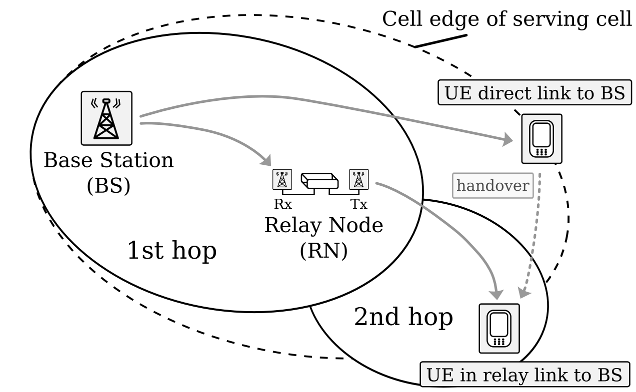

Fig. 1. Relaying scenario: the user equipment (UE) is either connected to the BS in the access link or 1st hop, or to the relay node (RN) in the relay link or 2nd hop with possible handover support for throughput maximization.

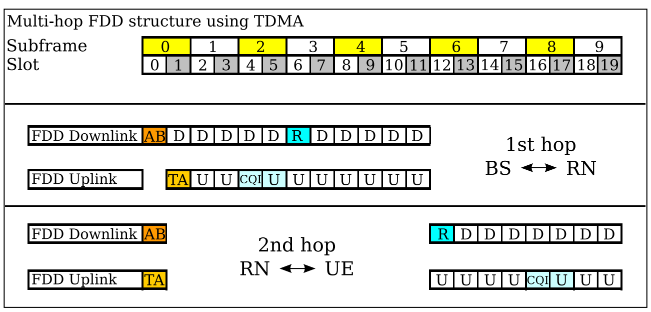

Fig. 2. FDD relay radioframe structure for a 10 ms radioframe using TDMA, D-downlink data, U-uplink data, R-radio resource map, AB/TA-preambles, CQI-channel quality information.

duplex relaying constraint straightaway halves the throughput delivered to the UE which is also the case if the UE is served in the feeder link. The delay introduced by timesharing can be minimized by an alternating transmission slot pattern.

B. Link adaptation

The multi-hop testbed implements full decode and forward functionality. This incorporates independent channel quality information (CQI) feedback exchange between multi-hop relay node (RN) and base station (BS) as well as between user equipment (UE) and RN. BS and RN deploy frequency dependent link adaptation, bit-loading and spatial mode selection. The spatial mode selection allows single-stream or dual-stream transmission depending on the channel condition. On the MAC-Layer, a so-called rate pulling mechanism as described in [8] forwards service demands to users attached via RN. Both BS and RN utilize a greedy MAC scheduling approach for resource assignment in time, frequency and space domains. Scheduling decisions are based on CQI feedback. It is implemented in a closed-loop fashion and works independent for BS and RN.

C. In- and out-of-band relaying with handover

For the throughput analysis we differentiate between in-band and out-of-band relays. In in-band relaying, the feeder link, 1st hop, and relay link, 2nd hop, use the same carrier frequency and are separated in time domain. In out-of-band relaying, feeder link and relay link communication is performed on different carrier frequencies and may not be separated in time domain. Out-of-band relaying obviously requires additional frequency resources for the feeder link. The delay caused by forwarding between feeder link and relay link in out-of-band relaying can be reduced to a slot or subframe by implementation of an alternating forwarding mechanism. Here, 1st and 2nd hop alternate on a slot or subframe basis. In both relaying concepts, UEs can employ handover techniques to connect to the strongest link.

III. Measurement Test Bed

A. Berlin LTE-Advanced Testbed

For the experiments we used the *Berlin LTE-A Testbed*, which was installed in the center of Berlin throughout 2008. This testbed consists of three base stations (BSs) sites and nine sectors, see [9]. For the measurement discussed in this paper, the 30° north-east sector of the BS on top of the *Telefunken* building at the *Ernst-Reuter-Platz* was used. The measurements are limited to a single-sector single-user scenario without any interference from other BSs. The antennas are mounted on an antenna pole on top of the building, 85 m above ground. The carrier frequency is 2.6 GHz which is within the UMTS extension band. The BS antenna is a cross-polarized panel with 2 antenna elements and a transmit power of 43 dBm. The antenna is equipped with an electrical downtilt unit which can be used to adjust the antenna downtilt between 0°-10°. This highly directive antenna is a standard antenna used for future sectorized cellular urban deployments. The BS was used for the direct link connection to a UE, as well as for the 1st hop in the relay scenario, refer to **Fig. 1**. The transmit power of the RN is set to 23 dBm. For additional downlink system parameters refer to [8].

B. Relay node placement

The relay node (RN) was placed inside a measurement van and positioned as a fixed node at the cell edge. With a base station (BS) antenna downtilt of 1°, the cell edge was located at the *Pariser Platz*, see **Fig. 3**. This square is directly located at the *Brandenburger Tor*, which is in 3.9 km distance east from the BS. The *Pariser Platz* is surrounded by various tall buildings with heights ranging from 15 m to 20 m. To the east, facing the BS, the LOS path to the BS is partly shaded by the columns of the *Brandenburger Tor*. This monument has a height of 26 m and has 6 columns of 12 m height each. The relay node (RN) has 2 sets of antennas. The first set was used to establish the 1st hop, the second set of antennas was used to establish the 2nd hop. For the first set of antennas, 2 linear polarized planar antennas were used, which were mounted on an antenna pole well above ground at 3 m height. These antennas were placed in LOS to the BS for maximum capacity in the 1st hop. The second set of antennas was used to establish the connection for the relay link to the user equipment (UE). For this link, a cross-polarized antenna cube was mounted on

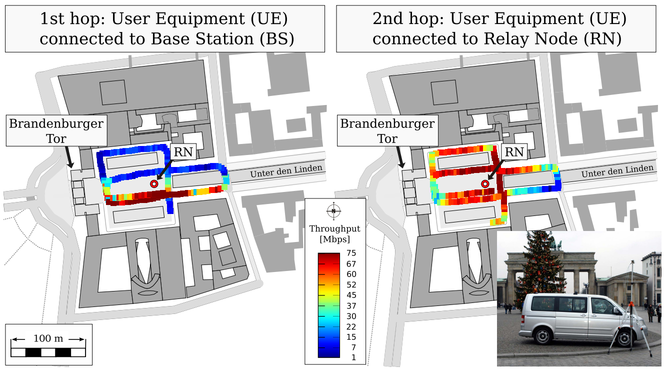

Fig. 3. Measured PHY layer data rates when moving along measurement track at the *Pariser Platz*, 1st hop (left) with 1°antenna tilt, 2nd hop (right), measurement van in front of *Brandenburter Tor* (lower right)

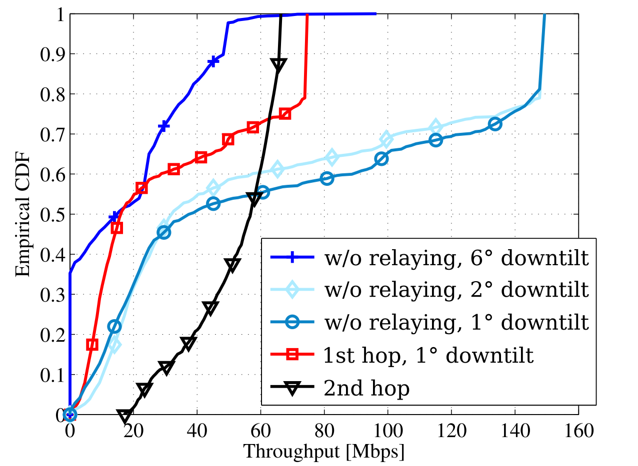

Fig. 4. Distribution of measured data rates along the measurement track for different downtilt angles, with and without relaying

an antenna pole at the same height as the antennas in direct link. For the 2nd hop, a single UE was installed inside a second measurement van and the UE antennas were mounted 20 cm above the roof of the van, approximately 2 m above ground. The RN was put at a fixed position. The second measurement van with the UE was moving on the same track around the *Pariser Platz* as shown in **Fig. 3**.

Several measurement runs were taken at a constant velocity of approximately 6 km/h. The track consisted of LOS and NLOS propagation condition to the BS covering a dynamic range of -54 dBm to -87 dBm at the receive antennas of the UE. Two sets of measurements were taken. One set without relay, were the UE was connected in the direct link to the BS. In the second set of measurements, the UE was connected via the relay node (RN) to the BS.

IV. Outdoor Results

A. Relaying without handover

The measured PHY layer data rates for the 1st and 2nd hop are shown in **Fig. 3**. Here, the data rates are color coded and plotted along the measurement track. The measured data rates range from 1 to 75 Mbps. From **Fig. 3 (left)** it can easily be seen, that high data rates in the 1st hop can only be achieved if the UE is in LOS to the BS. When moving away from the LOS path, data rates drop significantly below 20 Mbps. Several real-time measurement runs were taken with different downtilt angles $\beta = \{1°, 2°, 6°\}$ at the base station (BS) antenna. This was done to find a good position for the RN. The distribution of measured data rates on the PHY layer along the measurement track is shown in **Fig. 4**. With 6° downtilt, the UE suffers from outage probability in more then 35% of the cases. The first three measurements, blue curves, were done without the relay node (RN). Here, the user equipment (UE) was connected via direct link to the BS. In a second set of measurements, black curve, the BS downtilt for the first hop was fixed and the RN placed in an optimal position. Here, the feeder link could provide the RN with maximum data rate, approximately 75 Mbps, utilizing dual stream transmission with 64 QAM on each data stream. Note, the maximum achievable rate in our LTE system without relay is approximately 160 Mbps. The red curve depicts the data rate distribution of the UE when directly connected to the BS. From the distribution curves it can be concluded that the rate distribution is much smoother for the UE when connected to the RN which is shown by the steeper CDF. In this case, the data rate never drops significantly below 20 Mbps and the mean data rate is always above 50 Mbps. The smoother throughput CDF has its price: the cross-over point between black curve and light blue curves, with 1° or 2° downtilt, at about 60 Mbps shows that approximately 45% of users connected via RN lose data rate in this scenario when compared to the non-relaying case. On the other hand, if the UE is directly connected to the BS, the signal is shaded by buildings in more than 50% of the cases along the measurement track and the LTE user experiences in many places data rates well below 20 Mbps.

B. Relaying with handover

The throughput over the measurement track for the two sets of measurements is shown in **Fig. 5**. The measurement was taken in relay mode with 6/4 time sharing. The red curve shows the PHY layer data rate when the UE has a direct link to the BS, the black curve depicts the data rate when the UE is connected via the RN. In the 2nd hop, the mean received power over the two receive antennas never drops below -75 dBm and shows an average increase of 10 dBm when compared to the direct connection to the BS. Further rate gains can be achieved when utilizing handover to the feeder link 1,3 and back to the relay link 2. In this case, the UE benefits from LOS to the BS and the increased number of resources used for the feeder link resulting from 6/4 time sharing. The high data rates are achieved by the second spatial mode, in particular by cross polarization multiplexing, which can be utilized in more then 80% of the allocated physical resource blocks (PRBs).

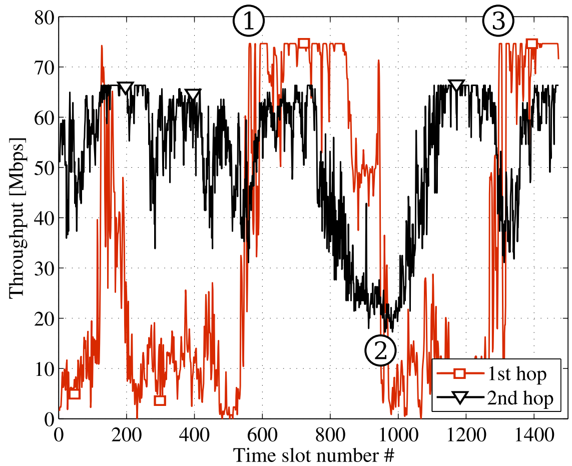

Fig. 5. Data rates along the measurement track, the colors coincide with the colors used in **Fig. 4**.

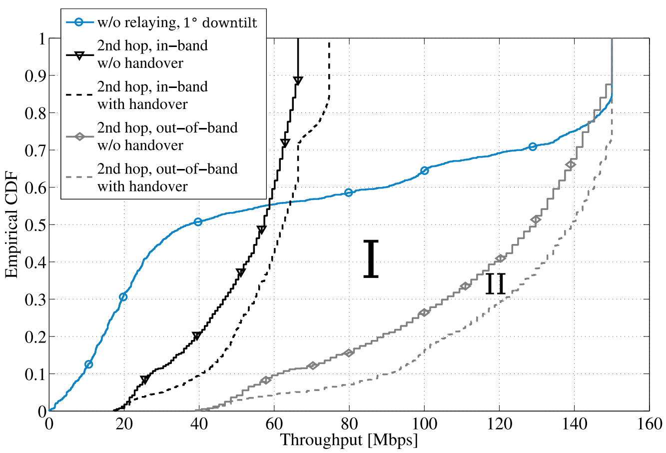

Fig. 6. Distribution of measured data rates, in-band vs. out-of-band relaying with and without handover between 1st and 2nd hop

C. In-band vs. out-of-band relaying

Fig. 6 shows the throughput distribution of the data rates for in-band and out-of-band relaying with handover. For comparison, this figure also contains the rate distribution for the best direct link, blue curve, and the 2nd hop in-band without handover from **Fig. 4**. Comparing the distributions for in-band relaying as implemented in the test bed, black curves, we see a throughput gain of approximately 9% from 57 Mbps to 63 Mbps when utilizing handover between feeder link and relay link. If we know consider out-of-band relaying, gray curves, the median throughput more than doubles for the cell-edge user. This is achieved by re-use of resources which were utilized by the feeder link and by reduction of the overhead caused by the in-band relaying implementation, e.g. signaling overhead. Remark: out-of-band signaling comes with higher costs in usage of frequency resources but shows an upper bound concerning the achievable data rate of the cell-edge user.

Finally, areas *I* and *II*, cf. **Fig. 6**, mark the data rate region between in- and out-of-band relaying. Data rates within these areas are only achievable if cooperative relaying or cooperative diversity approaches are employed. Here, cell-edge users can benefit from combining techniques, since the same information is transmitted in the 1st and 2nd hop. The RN can employ a more aggressive scheduling technique in order to compensate for a shorter duty cycle in the relay link.

V. Conclusion

Outdoor measurements show that data rates of above 60 Mbps are achievable with 20 MHz bandwidth and time-shared outdoor relaying. We showed that a rate gain of approximately 9% is achievable if handover between feeder link and relay node is employed. The effectiveness of wide-band relaying is useful for coverage holes in urban macro environments with a diameter of approximately 300 m. Multi-hop relaying is therefore a promising technology for range extension, delivering high data rates to the cell-edge. Such a deployment utility will therefore prove cost effectiveness by reducing new base stations installations and ensure fast deployment to meet coverage and capacity expectations in LTE cellular networks. These results complement LTE indoor relaying test trials described in [8]. Future work will consider cooperative relaying techniques especially if interference is introduced on the relay link. The focus is to improve data rates especially for users attached to the feeder link, which suffer under the TDMA relaying constraint.

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