Protocol Impact of LTE Relays on User Performance

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Abstract— **Relays are introduced for LTE Rel-10 in order to improve cell edge bitrates and coverage. 3GPP has specified both inband and outband relays. In this paper, we study the protocol level aspects of relays as well as cell-edge performance of a mobile terminal with system simulations. The results indicate that when a user is performing TCP downloads and uploads, in addition to potential subframe split between the backhaul and access link, also the adopted protocol solution and increased delays have impact on the user performance. Due to this, the bitrates may degrade even with outband relays if the UE having decent macro coverage is connected to a relay. However, when the UE has bad macro coverage, then there are gains from both inband and outband relays.**

Keywords; LTE, Relays, scheduling, TCP, HARQ, radio protocol

I. INTRODUCTION

3GPP has recently specified both inband and outband relays as a part of LTE Rel-10 [1]. By relays, the coverage and cell-edge bitrates of the LTE network can be improved. When a terminal connects to the relay, it does not see any difference as compared to connecting to a normal eNB. The relay is connected to the transport network via Donor eNB using an LTE connection as a backhaul link.

With outband relaying, the Donor eNB-to-relay (backhaul, Un) link operates in different carrier frequency as the relay-to-UE (access, Uu) link. If there is sufficient isolation, i.e., guard band between Un and Uu, both links can operate at the same time without interference and no time duplexing is needed. In an inband relaying system, relays transmit and receive in the same frequency band. If a relay transmits and receives at the same time, there is a risk of severe interference between the transmitter and the receiver side of the relay. Therefore, for deployments where there is not enough isolation between the backhaul and the access link, there is a need to create a time separation between backhaul and access link transmissions, both in DL and UL. The relay subframe allocation defines when the relay should receive in DL in the backhaul link. In other subframes, the relay can schedule DL traffic to its access UEs.

In this paper, the performance of LTE relays is studied. The focus is on adopted architectural and protocol solutions. We also discuss the impact of subframe allocation to different part of the radio network, such as HARQ protocol. With the system simulations, it is studied how bad the macro coverage of a User Equipment (UE) needs to be so that gains achieved due to improved geometry when connected to a relay are greater than possible loss due to subframe allocation as well as a doubled protocol stack. The LTE relaying performance has gained a lot of attention recently (see e.g. [2], [3]), but performance of adopted L1/L2 protocol solutions has not been studied so far.

The paper is organized as follows: In Section 2 we introduce 3GPP LTE relay architecture and protocol model, in Section 3 relay subframe configuration and its impact on HARQ protocol and in Section 4 UL scheduling protocol in a relaying scenario. The simulation scenario is described in Section 5 whereas results shown in Section 6. Finally, Section 7 makes a short conclusion.

II. RELAY PROTOCOL MODEL

The Relay Node (RN) operates as a standalone eNB connected to a Donor eNB (DeNB) over the LTE radio interface [1]. From a UE perspective, the cells of the RN are seen as normal cells and separate from the cells of the DeNB. The RN terminates all the radio protocol layers towards UEs, and the S1 and X2 protocols towards the rest of the network. See Figure 1 for illustration.

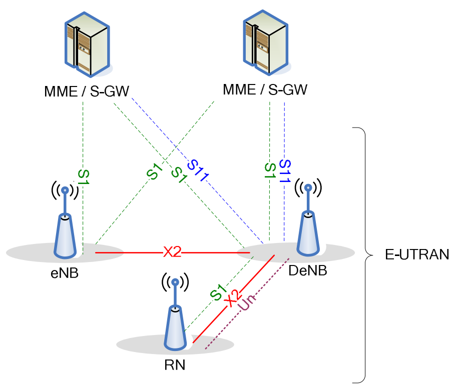

Figure 1. The relaying system defined by 3GPP [1].

The S1 user plane protocol stacks for supporting RNs are shown. There is a GPRS Tunneling Protocol (GTP) tunnel associated with each UE Evolved Packet System (EPS) bearer, spanning from the serving gateway (S-GW) associated with the UE to the DeNB. In the DeNB, the GTP tunnel is switched to another GTP tunnel, going from the DeNB to the RN (one-to-one mapping). The S1 user plane packets are mapped to radio bearers over the Un interface. The mapping can be based on the QCI associated with the UE EPS bearer. The Un link implements normal LTE L2 protocols such as PDCP, RLC, MAC, HARQ, and RRC, with minor additions to support Un operation.

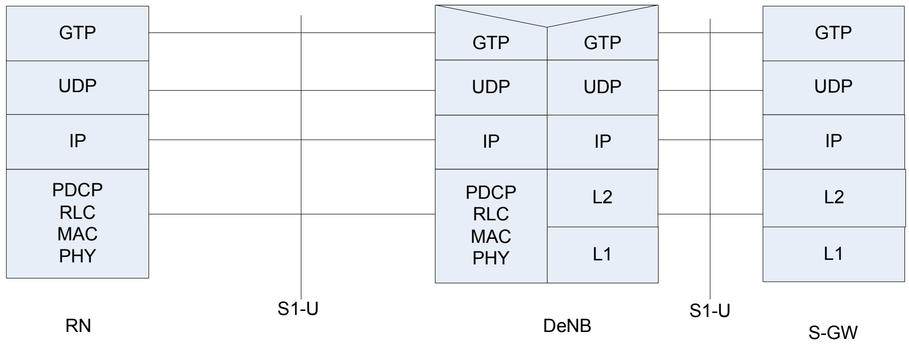

Figure 2. The protocol stack of the relaying system [1].

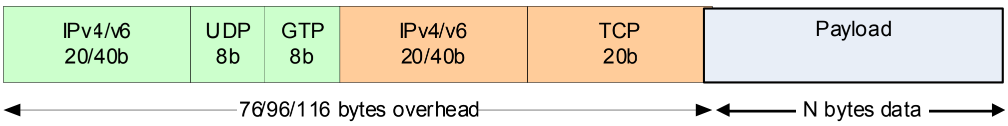

Figure 3. The protocol overhead in the case of TCP packet [4].

New protocol layers added to the Un link increase the amount of headers of each data packet. The protocol header format for transmission of a TCP packet over the Un link is shown in Figure 3. Compared to a normal eNB to UE transmission, the additional headers are IPv4/IPv6, UDP and GTP headers. Fortunately, the headers can be at least partly compressed, which decreases overhead to some extent. For the TCP segments, which are typically 1500 bytes, the header overhead is not significant. However, for TCP ACKs (typically 64 bytes) and for VoIP packets (typically around 33 bytes), the overhead can be significant even with compression.

III. RN SUBFRAME CONFIGURATION AND HARQ

For inband relaying, the interference between transmitter and receiver side is avoided by separating Un and Uu transmissions in time. To ensure that the Rel-8 UEs connected to the relay do not suffer from DL reception gaps of the relay, MBSFM subframes are utilized. During MBSFN subframes, the UE connected to the relay cell does not measure the reference signals over the whole subframe. Only transmission during the first symbols of the subframe and PDCCH control is expected. Hence, those subframes can be used for DL traffic between the DeNB and the relay. Description of RN physical layer can be found in [5].

The RN subframe configuration is signaled with Radio Resource Control (RRC) protocol from the DeNB to the RN. The configuration is a 8 bit long bitmap. The RN maps the bitmap to the possible MBSFN subframes to determine the Un DL subframes. The uplink subframes are implicitly defined from the downlink subframes. In FDD, if the subframe n is Un DL subframe, subframe $n + 4$ is Un UL subframe.

Time division of subframes to Un and Uu subframes have impact both on Un and Uu link. The consequences of the RN subframe allocation to HARQ protocol are very similar to the consequences of time division for UL/DL HARQ in LTE TDD:

1) DL HARQ. The HARQ feedback as response to DL transmission can be transmitted according to Rel-8 timing both on Un and Uu links due to n/n+4 rule mentioned above. It can be that DL HARQ retransmissions can not occur 8 ms after initial transmission due to lack of Un/Uu subframes, but this is not a problem for asynchronous HARQ operation in DL.

1) UL HARQ. In FDD LTE Rel-8, UL HARQ is synchronous having 8 ms Round Trip Time (RTT). In the Un link, this round trip time cannot necessarily be maintained because a Un UL subframe is not available after 8 ms. Thus, in the adopted solution in 3GPP, the HARQ RTT is not fixed in the Un link but depends on the RN subframe configuration. On the Uu link, due to desired backwards compatibility, the HARQ timing remains same as in Rel-8. For this reason, if the subframe after 8 ms from the initial transmission is not a Uu UL subframe, the HARQ retransmission needs to be suspended by 8 ms.

In Figure 4, allocation of subframes between the backhaul (Un) and the access (Uu) links is illustrated for one example RN subframe configuration bitmap [01110111]. In the backhaul link, the HARQ RTT for the initial transmission for Process 0 is 10 ms and for Process 1 it is 11 ms, instead of 8 ms in Rel-8. In the access link, the HARQ RTT for Process 0 is normal 8 ms. For the Process 3, the subframe occurring 8 ms after the initial transmission is not available for the access link. Thus the UL retransmission needs to be suspended by 8 ms and it will occur 16 ms after the initial transmission.

Radioframe	0										1										2									
Subframe	**0**	1	2	3	4	5	6	7	8	9	**0**	1	2	3	4	5	6	7	8	9	**0**	1	2	3	4	5	6	7	8	9
Potential MBSFN subframes		S	S	S			S	S	S			S	S	S			S	S	S			S	S	S			S	S	S	
DL Data Backhaul		D	D	D			D	D				D		D				D	D			D	D	D			D	D		
UL Data Backhaul						U	U	U			U	U				U		U				U	U			U	U	U		
UL HARQ ID						0	1	2			3	4				0		1				2	3			4	0	1	-	-
MBSFN configuration		S	S	S			S	S				S		S				S	S			S	S	S			S	S		
DL Data Access	D				D	D			D	D	D		D		D	D	D			D	D				D	D			D	D
UL Data Access					U				U	U			U	U	U		U		U	U	U			U	U				U	U
UL HARQ ID					0				1	2			0	3	4		1		5	6	0			7	1				0	3

Figure 4. Allocation of subframes for Un and Uu links and corresponding HARQ timing

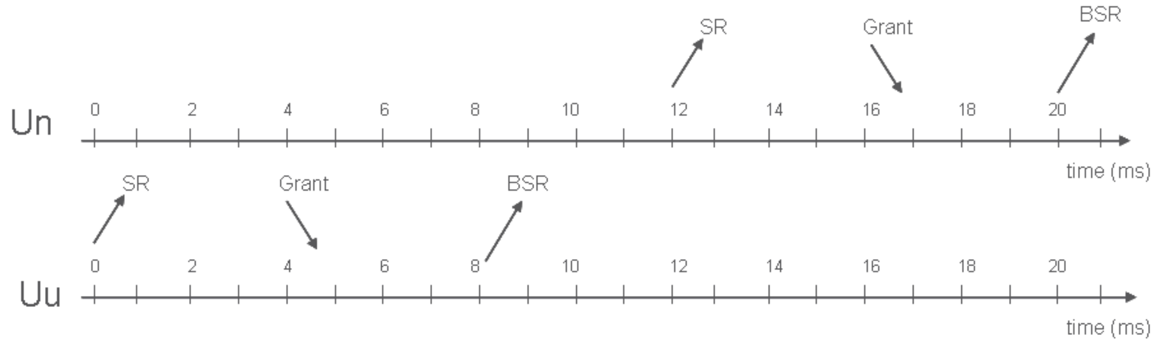

Figure 5. UL scheduling over Un and Uu links

IV. UL SCHEDULING PROTOCOL

When a UE has uplink data available, it transmits this data first to the relay node and the relay then transmits the data to the DeNB. The scheduling of the radio resources of the backhaul link is fully controlled by the DeNB. To enable uplink scheduling on the backhaul link, the scheduling mechanisms standardized for a UE are reused.

In the UL scheduling procedure in LTE Rel-8/9 [6], when new data arrives to the UL buffer, the UE triggers a Buffer Status Report (BSR) to report its buffer size. If the UE does not have UL resources to transmit the BSR, it triggers a Scheduling Request (SR). When the eNB has received the SR, it can schedule the UE and transmit an initial grant. Using the initial grant, the UE can finally transmit the BSR.

When the standard UL scheduling procedure is applied both in the Un link between the DeNB and the relay as well as in the Uu link between the relay and the UE, the delay over these two links increases clearly. As an example, see Figure 5. In the figure, the data arrives to the UL buffer of the UE connected to the relay. The UE transmits an SR to the relay. With some processing delay, the relay schedules the UE with an initial grant. With the received grant, the UE transmits a buffer status report and potentially some data, to the relay. When there is data in the relay buffer, the relay transmits an SR to the donor eNB which replies with the initial grant. With this grant the relay sends a BSR and potentially some data to the donor eNB. It can be seen that the user plane delay over the two links, Un and Uu, is over 20 ms which can negatively affect the performance of some applications.

There are some solutions to reduce latency in a relaying scenario:

1) Configure SR periodicity as short as possible both in Un and Uu links. In LTE Rel-8, the minimum value is 5 ms, whereas in Rel-9/10 it is 1 ms. A drawback of this approach is that the Physical Uplink Control Channel (PUCCH) load increases especially in the Uu link where the UE transmits SRs even in Un subframes.

2) Pre-schedule the relay node e.g. every Un subframe. A drawback of this approach is that the uplink load of the network increases meaning increased interference as well.

3) Trigger a premature SR/BSR in the relay node before UL data has actually arrived to the relay buffer. This can be based on e.g. the received SR.

It should be noted that when there are many UEs behind the relay, it can be that SRs are not needed due to frequent UL transmission in the Un link.

V. SIMULATION SCENARIO

Protocol performance of relays is studied in a simple scenario. The deployment consists of three links, the DeNB-UE link (denoted by G1), the DeNB-RN link (denoted by G2) and the RN-UE link (denoted by G3). See Figure 6 for illustration. Each link has a constant path loss. Fast fading (Typical urban 3km/h) is added on top of the path loss. Because there is only one user in the system, there is no interference. The UE can either be connected directly to the macro eNB (DeNB) or to the relay.

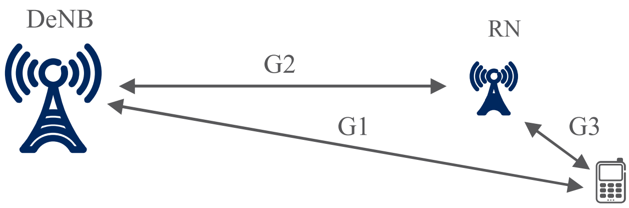

Figure 6. The studied deployment with one DeNB, one RN and one UE.

In the studied scenario, the UE position relative to the DeNB changes over simulation runs, that is, the UE moves further and further away from the DeNB. Because of this, the path loss G1 is increased from 110 dB to 160 dB. On the other hand, it is assumed that the UE is always close to the RN and G3 = 112 dB. This corresponds roughly to 3GPP model [7] where the relay is 50 m away from the UE (assuming NLOS, 20 dB penetration loss, 5 dB antenna gain). Finally, because it is assumed that the relay is an outdoor relay, the link G2 is better than link G1 having a path loss G2 = G1-25 dB. Path gain difference of 25 dB is close to the 3GPP model, assuming no penetration loss for backhaul (20 dB gain) and 5 dB from distance dependent gains. Other simulation parameters are typical and are given in Table 1.

Table 1. Simulation parameters

Parameter	Value
System Bandwidth	FDD: 5 + 5 MHz
Network layout	Simple with 2 nodes and 1 UE
Propagation model	Constant path loss
Multipath model	Typical Urban, 3 km/h
Antenna model	SIMO
Max. TX power	DeNB: 20 W RN: 1 W
Max. UL TX power	UE and RN: 0.25 W
Subframe allocation	Un: 50%, Uu: 50%
D-SR periodicity	Un and Uu: 10 ms
CQI periodicity	Un and Uu: 6 ms
HARQ transmissions	DL: max 7, UL: max 8
RLC mode	Acknowledged (AM)
Traffic model	FTP downloads/uploads, file size 1 MB.

VI. Results

In this section, the FTP download and upload performance is studied. We study a situation where the UE is directly connected to the macro eNB, i.e. DeNB, and a situation where the UE is connected to the RN. We study both inband and outband relaying. In the first case, the subframes are divided equally between Un and Uu links, whereas in the latter case, all subframes are available for all links. Note that in the case of outband relaying, all protocols related to Un link are still modeled and the backhaul is not considered as ideal.

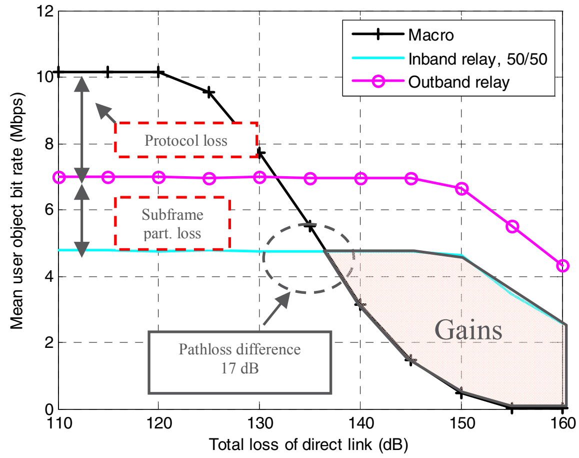

Figure 7. FTP download bitrate as a function of the macro link path loss. File size 1 MB.

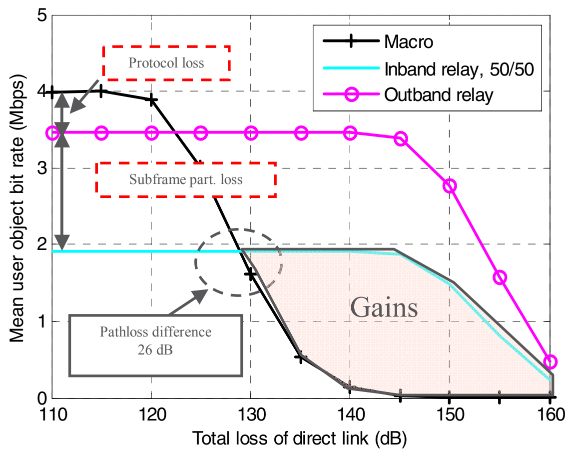

Figure 8. FTP upload bitrate as a function of the macro link path loss. File size 1 MB.

The FTP download and upload performance is shown in Figure 7 and Figure 8, respectively. In the y-axis the mean object bit rate is shown, where the mean object bit rate is the file size divided by download/upload time. In the x-axis the path loss of the direct link from the macro base station to the relay is shown. It can be seen that in both cases (download and upload), when the quality of the direct link is good, the relay decreases the performance significantly. This can be explained mainly by two issues:

1) **Protocol loss.** The relay increases user plane latency, as shown in Figure 5. In the slow start phase, the TCP sender

does not send TCP packets with full speed, but instead probes the bit rate of the underlying link by increasing the congestion window. In this phase, the TCP round trip time, constituting both from the user plane latency in the radio network as well as transport network and internet latencies, plays an important role. When the file size is rather small (here 1 MB), the maximum sending rate is not achieved during the download. The protocol loss is especially visible when comparing the performance of the macro eNB (DeNB) and the outband relay. In the both cases, the bit rates of the bottleneck links are the same, but in the latter case the data is transmitted over two radio links. Thus, performance drop is 30%.

2) **Subframe partitioning loss.** In inband relaying, the subframes are divided between Un and Uu links. In the studied scenario, the split is 50%/50%. If there would not be any protocol loss, subframe partitioning loss would be 50% when outband and inband relaying is compared. However, due to TCP, the radio link rate is not fully utilized especially during the slow start phase, and thus the loss due to subframe allocation is less than 50%.

Furthermore, it should be noted that when the link quality is better than 125 dB, improving it more does not improve performance because maximum transport block sizes as specified by 3GPP are already in use. However, this would not necessarily be true in an interference limited scenario.

When the path loss of the direct link increases over 138 dB in the download case and over 130 dB in the upload case, the inband relay gives higher bit rate than the macro eNB. In the switching points, the path loss difference between the access link and the direct link is 26 dB (download case) and 17 dB (upload case).

When comparing download and upload case, it can be seen that the protocol loss is smaller in the upload case. This can be explained by the lower maximum bit rates in general. Then also the TCP impact is smaller, due to the smaller bandwidth delay product. In addition, a lower transmission power in uplink is earlier limiting modulation and coding scheme and the selected transport blocks.

In Figure 9, the FTP download performance is studied for a bigger file size (10 MB). It is expected that the TCP impact is smaller and thus also the protocol loss. From the figure it can be seen that the performance of the outband relaying is closer to the macro case. However, the difference is still approx. 7%. When the protocol loss is smaller, the subframe partitioning loss in greater and approaches 50%. This effect can be seen from the same figure, when outband and inband cases are compared.

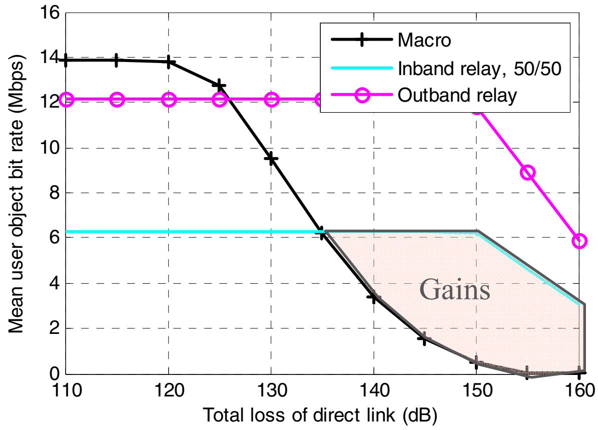

Figure 9. FTP download bitrate as a function of the macro link path loss. File size 10 MB.

VII. Conclusions

In this paper, the protocol aspects of LTE relays are studied. First the protocol and architectural models of LTE relays adopted by 3GPP is described. Then the cell-edge end user performance in a relaying scenario is evaluated with a system simulator including detailed modeling of LTE radio protocols. In the studied scenario, it is assumed that the UE is coverage limited, and the impact of the interference is negligible. It is showed that protocol impact of the relays, being mainly the increased user plane latency, impacts TCP downlink and uplink rates. Due to increased delays, the UE should be connected to the relay only when it has bad coverage and the path gain difference achieved due to being connected to the RN instead of the macro eNB is over 15 dB in download case and 26 dB in upload case. In other scenarios, if the UE is connected to the relay, the performance is worse, even when the relay is operating on the different frequency.

VIII. References

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