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Research Article

Dynamic Relaying in 3GPP LTE-Advanced Networks

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Relaying is one of the proposed technologies for LTE-Advanced networks. In order to enable a flexible and reliable relaying support, the currently adopted architectural structure of LTE networks has to be modified. In this paper, we extend the LTE architecture to enable dynamic relaying, while maintaining backward compatibility with LTE Release 8 user equipments, and without limiting the flexibility and reliability expected from relaying. With dynamic relaying, relays can be associated with base stations on a need basis rather than in a fixed manner which is based only on initial radio planning. Proposals are also given on how to further improve a relay enhanced LTE network by enabling multiple interfaces between the relay nodes and their controlling base stations, which can possibly be based on technologies different from LTE, so that load balancing can be realized. This load balancing can be either between different base stations or even between different networks.

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1. Introduction

The use of radio relaying with the deployment of relay nodes (RNs) for coverage extension in cellular networks is not a new concept [1]. Apart from the main goal of coverage extension, enabling relaying in a cellular network can also help in the provisioning of high data rate coverage in high shadowing environments (e.g., indoors) and hotspots, reducing the deployment costs of cellular networks, prolonging the battery lifetime for user equipments (UEs), and generally saving power by reducing the overall transmission of cellular networks and enhancing cell capacity and effective throughput. Figure 1 shows the most typical usage scenarios for relaying.

Many of the earlier studies on relaying were rather theoretical and mainly concerned with information theoretic capacity limits. It is only recently that practical solutions have been proposed due to the maturity of cellular systems and the ever increasing demand for high data rate services [1–4]. After being carefully considered in prestandardization activities like the IST-WINNER project [2], relay enhanced systems are achieving the level of maturity needed in ongoing

standardization activities. The best evidence of this maturity is the IEEE 802.16j standard specifying relaying for the mobile WiMAX (802.16e) systems [3, 4].

The 3rd Generation Partnership Project (3GPP) is currently finalizing the specification of UTRAN long-term evolution (LTE) Release 8. Discussions have already started regarding LTE-Advanced standardization, and relaying has been proposed as one of the key candidate features [5, 6]. However, for the sake of economic viability, LTE-Advanced is required to be as much backward compatible as possible with LTE Release 8. This is especially important from the UE side, as it will allow users to benefit from relaying with their Release 8 terminals. Due to the assumption of focusing this paper on LTE-Advanced we refer to a base station by the 3GPP term enhanced Node B (eNB).

Several kinds of relaying systems have been proposed, the most representative ones being simple repeaters that amplify and forward the received signal, decode and forward relays that decode the received signal and regenerate it, and relays that support the full functionalities of an eNB [7]. From a system level point of view, relaying can be performed either in a *conventional* or *cooperative/collaborative* fashion.

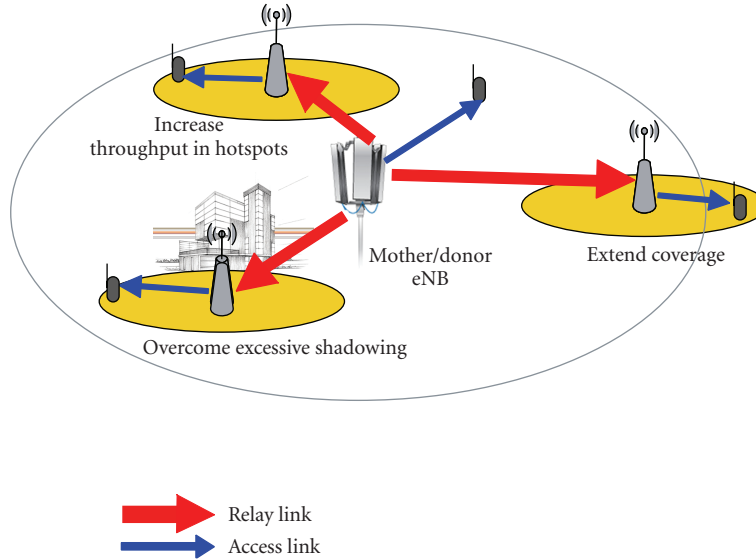


FIGURE 1: Examples of an LTE radio access network deployment with fixed relay nodes.

In conventional relaying, the UEs are receiving data either from the serving eNB or the RN. In collaborative relaying, on the other hand, the UEs can receive and combine the signals from several RNs and the eNB [8]. A conventional relaying scheme is assumed in this paper to support backwards compatibility as it is simple and practical for transitioning LTE into the realm of multihop systems.

Relaying can be realized at the different layers of the protocol stack. A simple amplifying and forwarding RN can be realized at the Layer 1 (L1) of the protocol stack where the RN is required to have only (some part of) the PHY layer. Layer 2 (L2) RNs, which include the protocol stack up to the Medium Access Control (MAC)/Radio Link Control (RLC) layers, enable the possibility of decentralized radio resource management (RRM). Layer 3 (L3) or higher layer RNs could almost be considered as wireless eNBs and support all the protocol layers of normal eNBs, except that they will not require an expensive backhaul as in a normal eNB (i.e., the backhaul between the RN and the eNB will be based on the LTE air interface instead of microwave or wired interface), and they are assumed to have low transmission power capabilities. Unless otherwise specified, L2 or L3 relays are assumed throughout this paper.

We consider a simple scenario where at most two hops are allowed. Such a scenario is most attractive from a practical perspective because the system complexity is strongly related to the number of hops. Throughout this paper, we refer by direct link to the connection between an eNB and a UE, by backhaul or relay link to the connection between an eNB and an RN, and by access link to the connection between an RN and a UE.

The aim of this paper is to present an architecture that will enable dynamic relay deployment in LTE networks in a backward compatible way from the UE's point of view. In particular, dynamic backhauling, multimode relay, and distributed relaying are components of the designed

architecture and separately treated in the following sections. The rest of the paper is organized as follows. In Section 2, a simple extension of the basic LTE architecture to enable static deployment of fixed RNs is described. Section 3 extends this architecture to support dynamic backhauling. The possibility of using multiple air interfaces for optimal radio resource utilization is described in Section 4. Section 5 extends the multiple interfacing concepts in order to support the integration of relaying and home eNB into a single equipment. After discussing distributed relaying where a relay node can be served via several eNBs in Section 6, a conclusion is given.

2. Architecture for Static Relay Deployment

Figure 2 shows the architecture of an LTE network extended to support static relay deployment. The gateways are in charge of functions such as nonaccess stratum signalling, mobility, and bearer establishment/maintenance [9]. Due to the conventional nature of the relaying, a UE is connected either directly to an eNB or an RN, but not to both. All the traffic intended for a relayed UE is always routed to the controlling eNB (also referred to as “mother eNB” or “donor eNB”) of the concerned RN by the gateways and then routed to the RN via the donor eNB.

As in Release 8 LTE, the eNBs control the radio resource management (RRM) of the system [9]. Additionally, they are also responsible for the configuration and controlling of the RNs and their resources, routing of traffic to the RNs, ensuring reliable communication links between the eNB and the UE by means of outer Automatic Repeat reQuest (ARQ), flow control to allow smaller (and cheaper) buffers in the RNs, and so forth. Thus, the gateways do not necessarily have to be aware of the existence of RNs in the system.

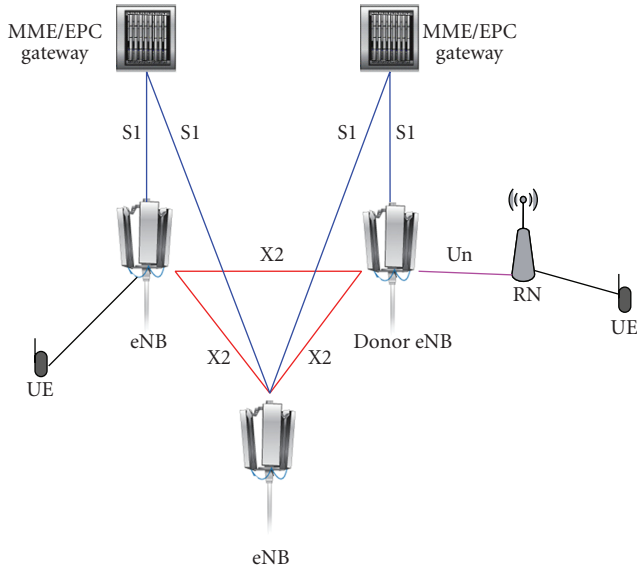


FIGURE 2: Architecture for relay enhanced LTE network with fixed RN deployment.

The most important task of the RN is to forward data between the eNB and the UE. It is supposed that standard LTE Release 8 UEs should be able to communicate via the RNs. An RN should thus be capable of broadcasting system level information in the same manner as the eNBs so as to appear as a normal eNB to the UEs. Due to this, the UE-RN interface should be the same as the Release 8 UE-eNB interface [9, 10]. The L3 RNs considered here also support decentralized RRM. That is, the RNs are responsible for scheduling packets on the radio interface using the resources that have been reserved to them by the eNB.

Since the link between the eNB and RN carries both the traffic to the UEs and the traffic needed to control the RNs, this interface will have different characteristics than the LTE Release 8 air interface. It is referred to as the Un interface and it can contain the functionalities of both the S1 interface (Gateway-eNB: for control information as well as for data transport), the X2 interface (eNB-eNB: for forwarding user data, similar to the case of handover forwarding in LTE Release 8), as well as the LTE air interface (eNB-UE: for control information as well as for data transport).

In the architecture described so far, the RNs are assumed to be deployed by the operator on certain locations, especially on hotspots and locations that are highly likely to suffer from coverage loss (cell edge and high shadowing areas), and each RN is associated with a donor eNB. However, such a static association limits the flexibility/efficiency of the system.

3. Dynamic Backhauling

Enabling dynamic backhauling of RNs is attractive for several reasons. The donor eNB may be overwhelmed by a high load within its cell, while a neighbouring cell is completely unloaded. Moreover, static association limits the system to support only stationary RNs, and thus mobile RNs (e.g., RNs

attached to trains) cannot be used. Running a system with several lightly loaded cells is highly energy inefficient [11] and efficiency can be enhanced by powering off some of the eNBs or RNs in the system (e.g., during late night hours on weekdays) and concentrating the system load on few eNBs. If the eNBs that are to be powered off are relay enabled, it would also be beneficial to associate the RNs in these cells with other eNBs that are still active, instead of rendering them useless when their donor eNBs are powered off. Finally, dynamic backhauling, where the RNs can work in plug-and-play fashion, is a requirement in a Self-Organizing Network (SON), which is one of the important features demanded by cellular operators for future LTE releases [12].

In order to enable dynamic backhauling, a mechanism is needed for the RNs to discover relay-enabled eNBs that can act as their donor eNBs. The eNBs that support relaying can inform RNs about their relaying capability by including this information in the message blocks they broadcast regularly to the whole cell. This will not affect backward compatibility as the UEs can simply ignore this extra information. As an alternative, the RNs can query the eNBs to see if they support relaying using a new Radio Resource Control (RRC) protocol procedure. eNBs that do not support relaying will not recognize this message and will thus ignore it.

The information element for identifying relaying support that is sent by eNBs could include several entries such as the cell load, geographical locations, where the eNB is experiencing capacity/coverage problem and hence support by an RN is highly needed, supported mode of relaying (L1, L2, L3, etc. . .), energy saving settings, if any (e.g., when the eNB is scheduled to be powered off next).

When an RN is powered on, it is required that it has to be associated with an eNB before it can become fully operational. The reason for this is that it is not yet connected to the core network side and relaying a UE's connection is feasible only through the donor eNB. If relaying capability is discovered through broadcasting, the RN, when powered on, will listen to the different relay support broadcast messages of neighbouring eNBs and will select the one that satisfies acceptable criteria for donor eNB selection. On the other hand, if relaying capability information is to be acquired via a RRC request procedure, the RN has to send the request to the neighbouring eNBs that it can detect and then it will select the one that satisfies acceptable selection criteria.

Once the RN has identified the eNBs that support relaying, it can select its donor eNB based on several criteria. It can select the eNB with the best path gain (which in many cases will be the cell in which the RN is geographically located). Apart from the path gain, the interference and the load can also be taken into consideration to find the eNB that can provide the highest backhaul data rate to the RN. The one with the highest load can also be selected as the donor eNB, as it might probably need some load sharing. If the relaying capability information contains locations where coverage/capacity problems are being experienced by the eNBs, this can enable the RN to associate with the eNB that it can help optimally. Additionally, if energy saving settings are provided, it is also beneficial to select an eNB that is not scheduled to be powered off soon in order to

avoid unnecessary handovers. A combination of several of these criteria mentioned perviously can also be used in the decision process.

Although it is not within the scope of this paper, it is very informative to mention that the overall radio resource can be partitioned between the access links and the relayed links in an orthogonal fashion (also referred to as *Hard reuse*) where the relay and access links use different resources, or a nonorthogonal resource scheme (also referred to as *Soft reuse*) where the relay and access links share the radio resources to some extent. If multiple RNs are deployed within a cell, spatial separation between the access links of the RNs can guarantee a safe reuse of the resources. The partitioning can be done either in a fixed way where a subset of the radio resources is reserved for each RN or in a dynamic way where the needed resources are allocated per scheduling period. The resource splitting can be done either in a time division multiplexing (TDM) or frequency division multiplexing (FDM) manner. The splitting of resources (either in frequency or time domain) will require the use of two time or frequency slots (one for relay link and one for access link) instead of one slot for a direct connection. However, due to the high channel quality of the relay link and the access links (since it is UEs with the worst direct link quality to the eNB that end up being connected to the RN), there will be overall gain in the end-to-end throughput [13].

Dynamic backhauling implies the possibility of handing over an RN and all its associated UEs to another eNB. In order to support this, the handover mechanism of LTE specified in [9] has to be extended, as shown in Figure 3 [14]. Based on the measurement results it is getting from the RN, and also on other conditions such as energy saving settings and load-balancing communication from neighbouring cells, the donor eNB (source eNB) decides to hand over the RN to another eNB (target eNB). This handover decision is communicated to the target eNB. In this handover request message, the donor eNB summarizes the total resources required to accommodate the RN to be handed over including its associated users.

The donor eNB can at least indicate the overall (backhaul) traffic demands of the RN and its cell with necessary UE contexts in detail. It can also inform the target eNB the RN location and RN measurement reports about the RN-target eNB radio link. The target eNB can use this information to estimate the required radio resources to admit the RN.

If the required resources are available, which is checked by the admission control procedure in the target eNB, a handover request acknowledgement message is sent to the source eNB. The source eNB then sends a handover command to the RN (RRC connection reconfiguration including mobility control information), and from then on, the data destined to the RN is forwarded to the target eNB until the handover process is finalized.

Upon the reception of the handover command, the RN reacts differently depending on the scenario: the source and target eNBs have the same modes of operation (i.e., they both use the same duplexing mode, frame structure, etc.), and

they are also synchronized with each other; or the two eNBs operate in different modes, or they are not synchronized.

In the first case, the RN can maintain its timing, and the UEs that it is serving do not have to change their timings. Thus, the UEs do not have to be aware of the RN handover, that is, the handover is transparent to the UEs, and as such the messages in the orange box in Figure 3 are not required. Thus in the first case, the RN detaches itself from the source and immediately starts synchronizing with the target when it gets the handover command.

The second case is more complex as the RN has to change its timing and possibly other parameters such as frame structure, cell ID, scrambling code, and reference signal structure. In this case the RN has to command the UEs to handover to the new cell, that is, the RN after the reconfiguration and timing changes. The messages inside the orange box in Figure 3 are thus required. The handover command has to be sent to the UEs before the reconfiguration of the RN, that is, before the RN synchronizes to the target eNB, because the RN will typically change its timing or other configurations at that time.

Once the RN has achieved L1/L2 synchronization with the target eNB (and in the second case, in addition to this, also when all the UEs have resynchronized with the RN), the RN sends a handover confirmation message (RRC connection reconfiguration complete) to the new donor eNB. This confirmation is a composite message that includes information about each UE that is being served through the RN. The new donor eNB then sends out a path switch request to the Mobility Management Entity (MME), which initiates a user plane update request to the serving gateway. User plane update is then performed by the serving gateway for each UE indicated in the composite handover confirmation message. A user plane update basically switches the downlink data path to the target eNB. The serving gateway then sends “end marker” packets to the source eNB, to indicate that the old path is not going to be used anymore for the concerned UEs. After the route update is performed, packets destined to the UEs served by the RN will be properly routed via the new donor eNB.

The source eNB is then advised that it can release the resources pertaining to the RN (Release RN-UE context, as the RN is seen as a special UE from the eNB's point of view), and the link between the source eNB and the RN is released. After the forwarding of the final packet in flight to the target eNB, the final resources are released by the source eNB and the handover is finalized.

It should be noted that the load-balancing handover described here is not as delay critical as a regular handover of a UE. Thus, enough time could be taken to negotiate and settle resource issues for the RN cell and its UEs. Upon receiving a handover command, the RN might have to take time to reconfigure its cell and UEs first, some UEs might need to be downgraded or even dropped due to lack of resources.

This need to downgrade or drop calls can be gathered from some indication about the available resources for the RN and its UEs in the new target cell, which can be included either in the HO request acknowledged command or an

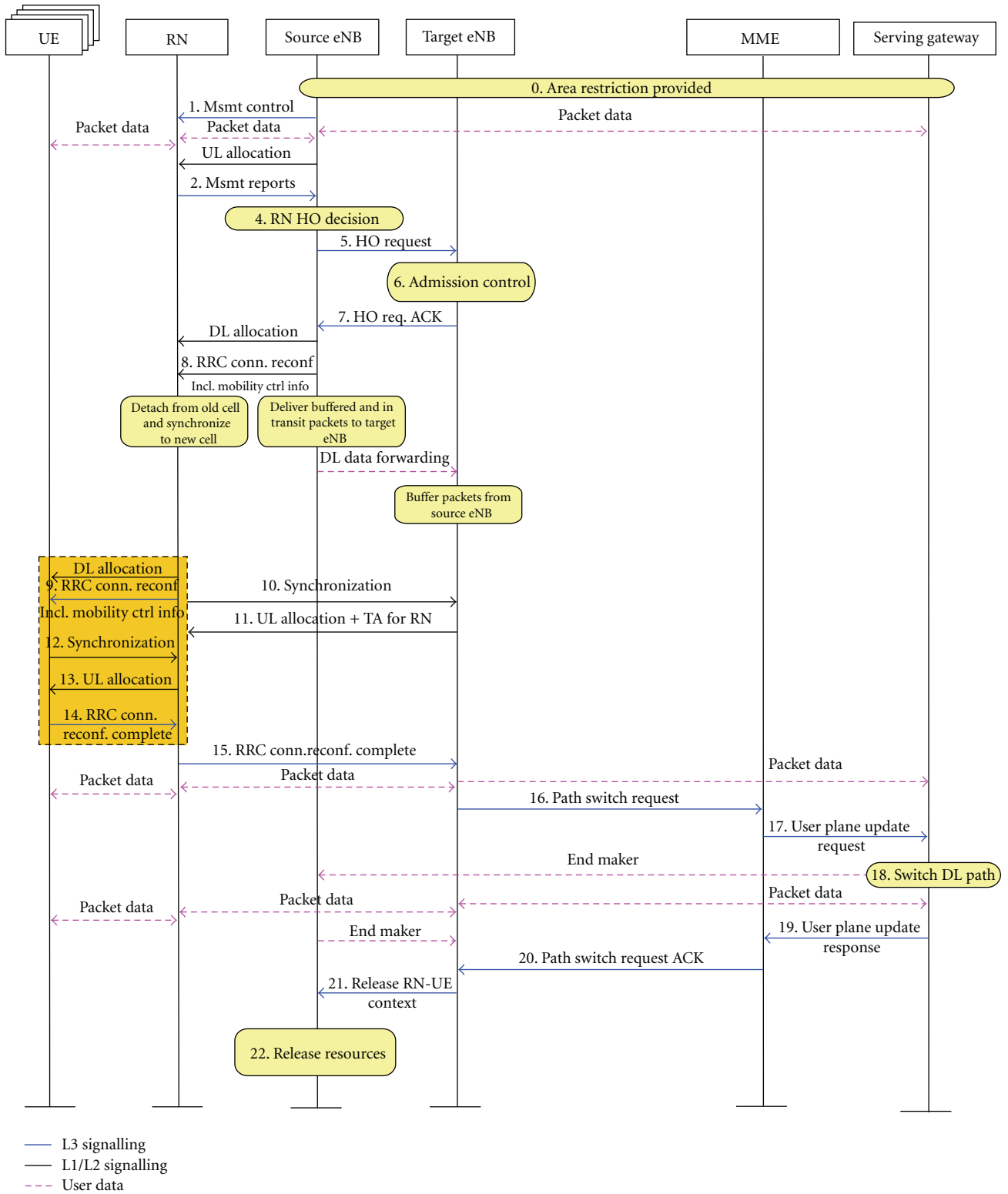


FIGURE 3: Handover of an RN and all its associated UEs in an LTE network that supports dynamic RN deployment.

additional signal sent from the target eNB. However, the RN might avoid these downgrades and call drops by initiating a separate handover of the concerned UEs to another RN or eNB. These additional handovers can be initiated either after the RN handover is finalized or even before that once the HO command is received. Doing these additional handovers before the RN handover is finalized will save the UEs from performing two consecutive handovers and thus it reduces the total handover delay. However, such pre-emptive handovers are not foolproof as resource reallocation and repartitioning after the RN handover is finalized might have been sufficient to provide the required quality for all the connections. Thus, the pre-emptive handovers should be initiated only when there is a very high disparity between the required resources of the relayed UEs and the available resources in the target cell.

Some UEs may have to be assigned to different resources, if the currently used resources collide with resources used for other purposes in the new eNB, for example, resources that the target eNB intends to use to communicate with the RN. It is possible to assign resources fully dynamically in LTE via fast scheduling and these allocations can be changed accordingly on the fly. On the other hand, for semipersistent scheduling, UEs are granted resources for a longer time interval and these grants need to be reconfigured for the handover. This can possibly happen even before handover initiation (i.e., before sending the handover command to the UE), immediately afterwards or after the re-establishment of the link.

Apart from dynamic association of RNs and eNBs, dynamic backhauling also allows the operator to activate and deactivate RNs in a certain area as needed in order to deploy extra capacity needed to satisfy peaks in users' demand, but at the same time save energy when it is not needed by simply powering off unnecessary RNs. Figure 4 illustrates the deactivation procedure.

Based on the measurements from the RN and load conditions in neighbouring cells, the donor eNB decides to deactivate the RN, as shown in Figure 4. The donor eNB sends out a deactivation command to the RN, and the RN initiates a handover procedure for all its users. Once the handover for each relayed UE is finalized, the RN deactivates itself and sends a deactivation confirmation message to the donor eNB.

The deactivation command from the donor eNB to the RN can contain parameters needed for future reactivation of the RN. This can include timer values such as a sleep interval during which the RN completely shuts down its transceiver, and also on-duration periods during which the RN will listen on a common control channel such as a paging channel to determine if the donor eNB is trying to reactivate it. This procedure can be done in a way similar to the Discontinuous Reception (DRX) procedure of LTE [9].

4. Multimode Relays

As one of the main driving forces behind the deployment of RNs is the low infrastructure cost, RNs in LTE-Advanced

use in-band wireless links based on the LTE-Advanced air interface instead of using wired links or dedicated out-of-band (e.g., microwave) wireless links.

Though this is a cheap and simple solution, there might be a need to support out-of-band wireless links. This is especially significant in scenarios/durations where the radio resources are limited and not enough resources can be reserved to the backhaul link without compromising the quality of users that are directly being served by the eNB. Thus, it can be beneficial to use multiple interfaces in the backhaul link, not only to increase the system performance, but also to add robustness to the system by switching between the interfaces, or even sharing the load between the multiple interfaces when the need arises. The prevalence of overlay networks where multiple networks (e.g., GPRS, UMTS, HSPA, etc.) are available at a given site facilitates the possibility of switching/load-sharing.

Figure 5(a) shows the different interfaces in a relay enhanced LTE network. As can be seen in the figure, the backhaul link is using the LTE-Advanced air interface while the access link between the RN and the UE is using LTE Release 8 air interface for backward compatibility purposes. In Figure 5(b), we propose a new architecture where additional interfaces are available (Ib2 to IbN in the figure) in the backhaul link apart from the LTE-Advanced air interface.

Multimode RNs should coexist with single mode RNs (those that support only the LTE-Advanced interface), and as such, it is necessary for the eNBs to find out the interfacing options available at the RN. The exchange of the interfacing capability of the RN can be done either during the association of the eNB and the RN (i.e., when the RN is first activated or handed over to another eNB as described in Section 3), or using separate *RRC interface capability* messages after the association is finalized. This interface capability request will be ignored by single mode RNs as they are not aware of this procedure, and thus the eNB can safely assume that the concerned RN is a single mode RN if it does not get a response after a certain number of repetitions of the interface capability request.

The LTE-Advanced air interface is the default interface to be used between the donor eNB and the RN. However, once the association procedure is complete and the donor eNB is aware of the interfaces supported by the RN, the interface to be used can be modified according to system need. The interface selection decision is controlled by the eNB.

The optimal interface can be chosen based on several criteria. The interface that belongs to the network with the lowest load, or in other words, the network that can provide the highest capacity for the relay link is an obvious choice. However, the cheapest network, from the operator's operating expense (OPEX) point of view, or the network that optimizes certain resources like energy can also be chosen.

The main advantage of using multimode RNs is to dynamically modify the interface to be used for the backhaul link for optimum system performance. Thus, there is a need to deactivate the currently active interface and (re)activate another interface. The decision to change the interface is done in a similar fashion as in the case of the interface

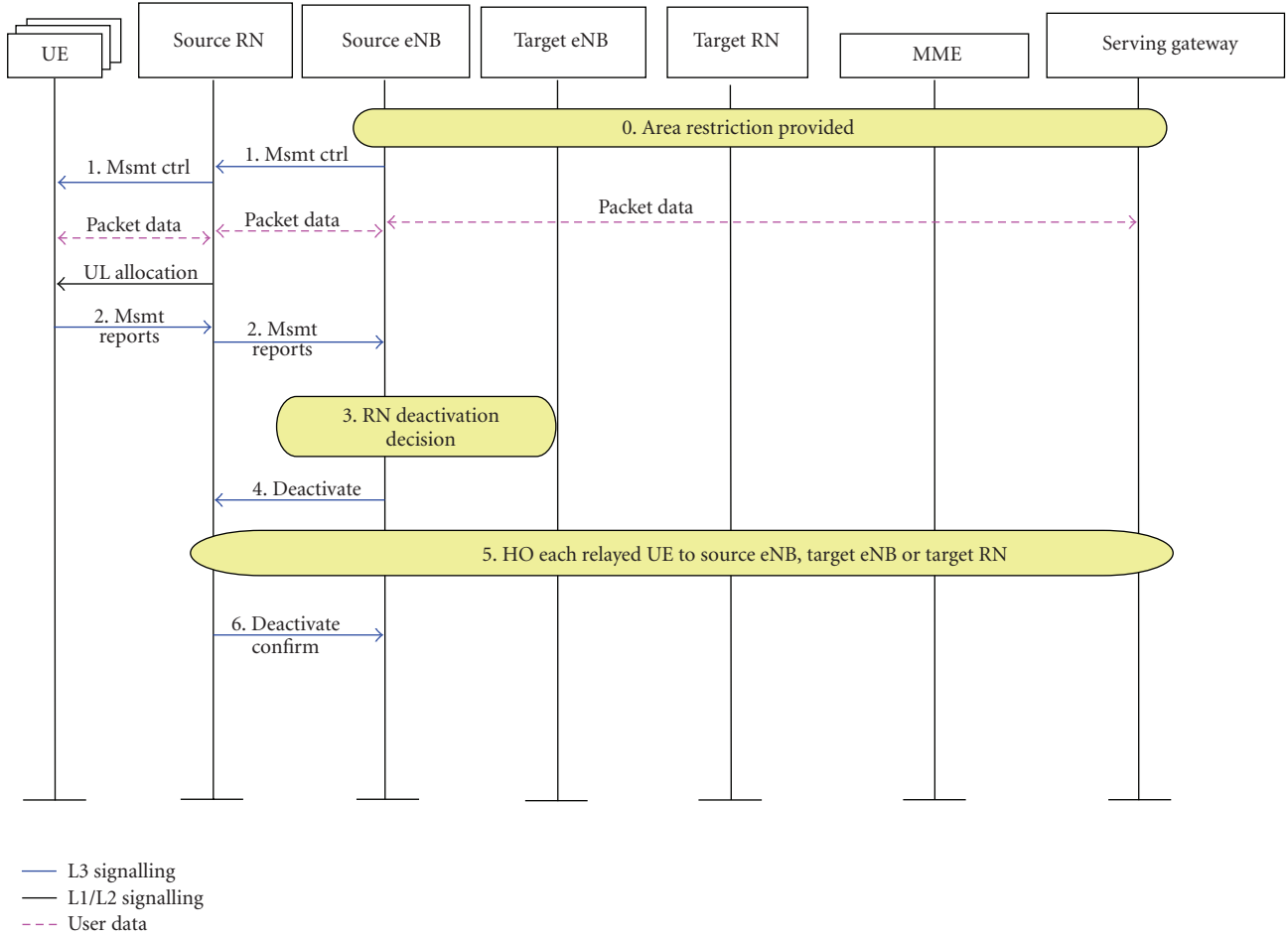


FIGURE 4: Deactivation of an RN in an LTE network that supports dynamic RN deployment.

selection procedure, that is, based on load, throughput, cost factors, or other reasons.

Based on the aforementioned factors, measurement results that it is getting from the RN, and other conditions such as load-balancing communication from neighbouring cells, the donor eNB decides to change the interface for the backhaul link. This decision is communicated to the RN and the RN deactivates the current interface and (re)activates the new one. The relayed UEs should not be aware of the interface changes.

Several factors have to be considered in order to make sure that no user data is lost and all active bearers that belong to relayed UEs are not disconnected. Adequate radio resources have to be allocated on the new network before the interface modification is initiated to ensure that the Quality of Service (QoS) of active bearers will still be satisfied. Also, any outstanding data on the old interface should be forwarded to the new interface, both in the donor eNB and RN, before the old interface is deactivated.

Though the possibility to switch between the different interfaces available to a multimode RN is important to transfer the connection to the network for optimal overall system utilization, there might be cases when one network is not able to provide all the needed resources for all the

relayed UEs. Thus, it is essential to enable the simultaneous activation of multiple interfaces of a multimode RN.

The measurement reports from the RNs that may lead to interface activation/deactivation can be sent either periodically or triggered when certain thresholds related to the allowable load values on a given interface are reached. A combination of periodic and event based measurement reporting can also be used. For example, periodic reporting with a long reporting period can be used under normal conditions to minimize measurement overhead, but threshold-based triggering can override the periodicity and send the reports in order to avoid unnecessary delay in the interface activation/deactivation which can possibly lead to the downgrading or even the dropping of active bearers. Just as in the case of a simple UE handover between two eNBs, ping-pong effects can be prevented using hysteresis thresholds.

The two main reasons for activating multiple interfaces are either that a new bearer has to be established by a relayed UE and there are not enough resources for the backhaul link for this connection, or that a new bearer is to be established by a directly connected UE but there are not enough radio resources, unless some resources being used for the backhaul link are freed. In the first case, the new bearer will be

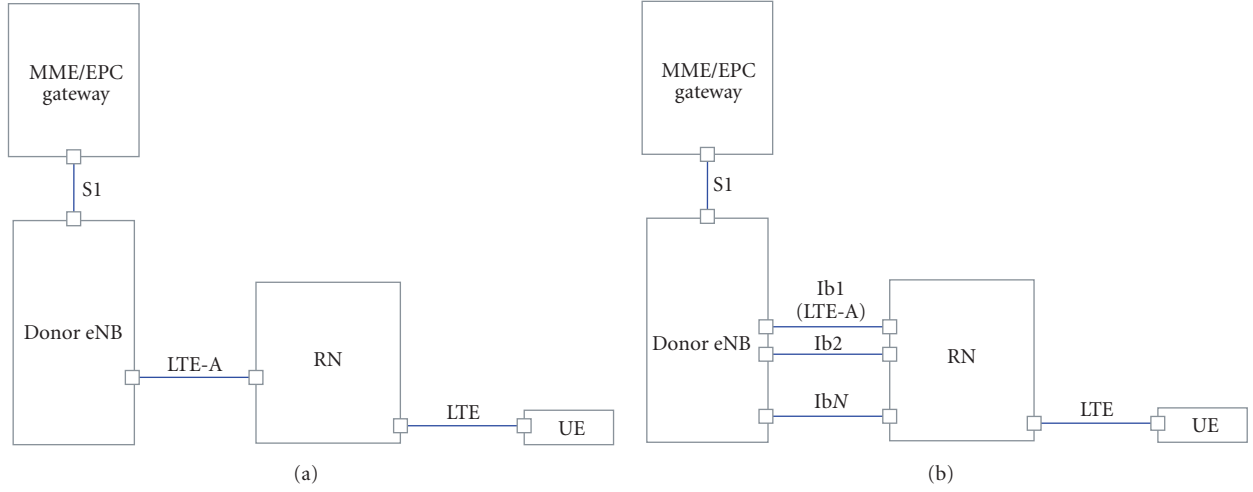


FIGURE 5: Interfaces between different network elements, (a) single mode RNs, (b) multimode RNs.

associated with the new interface and the rest of the bearers is not affected. In the second case, on the other hand, the donor eNB has to select a relayed bearer or even directly connected bearers which have to be transferred to the new network, so that the new direct bearer can be admitted to the cell. Measures have to be taken on the data of the selected bearers in order to avoid user data loss and dropped bearers.

5. Relay Node-Home Enhanced NB Integration

3GPP is currently standardizing home eNBs, also known as “femto-cells” [15]. Home eNBs are similar to WLAN access points and will be installed in residence and office buildings where there is already an access to Internet, for example, via a wired system. They will appear as normal eNBs to the UEs and they will access the core network of the operator via the Internet. Generic Access Network (GAN), also known as Unlicensed Mobile Access (UMA), is chosen by 3GPP as the way to provide the interfacing to the operator’s core network through the Internet. Though home eNBs seem to be an attractive solution for nonreal time (NRT) services, there might be some real time (RT) services that have very strict QoS requirements that might not be met via the Internet connection (e.g., when there is congestion). In order to resolve this issue, we extend the concept of multimode RNs described in Section 4 to support also home eNB functionality.

Figure 6 shows a multimode RN enhanced to support home eNB functionality. As can be seen from the figure, there is a new interface, which we refer to as $S1_{RN}$, between the RN and the core network elements using DSL or cable, in a similar fashion as a home eNB. Note that $S1_{RN}$ does not necessarily have to be a wired interface, as long as it gives a direct connection to the Internet, which is then routed to the core network of the operator. Note that L3 or higher layer relays are required to enable this functionality as routing via the Internet is required.

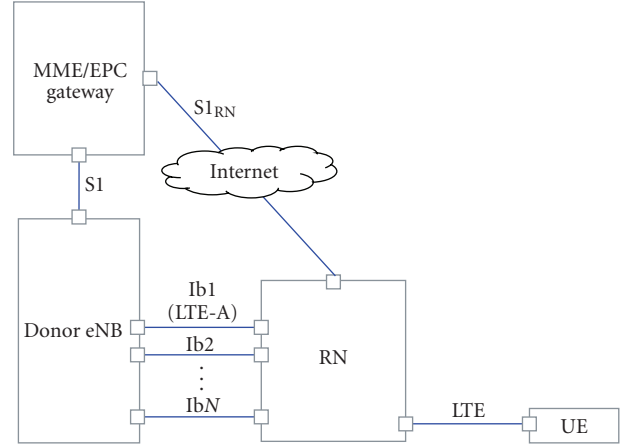


FIGURE 6: A multimode RN enhanced with home eNB functionality.

Such an RN that is equipped with a wired/wireless access to the Internet can act as a home eNB when the need arises, and can operate in several modes.

- (1) It can use the Internet as an alternative interface to the LTE-Advanced interface; that is, the data for the relayed users will be routed from the eNB to the RN via the core network and the Internet, and the RN forwards it to the relayed UEs via the LTE air interface (and vice versa for uplink traffic).
- (2) It can use the Internet for load balancing where some of the bearers will be supplied via the Internet as in the first case, and the rest is provided by LTE-Advanced or/and the other wireless interfaces in the backhaul.
- (3) It can operate as a stand alone home eNB where the RN is directly connected via the $S1_{RN}$ interface to the core network.

The first two options require that the system has to be configured to support home eNBs (i.e., connection to the operator's network via the Internet) and a modification in the GAN in order to route the data back and forth via the eNB instead of the gateways. This means, while the RN is connected to the eNB logically, this connection is realized physically via the Internet and the GAN instead of a direct physical link between the RN and eNB that has been assumed so far in the previous sections.

The third option is basically the same as a home eNB operation, and the donor eNB does not have to be concerned with the data for the relayed UEs any more as they are transported directly to the gateway without the need to reach the donor eNB. However, it is still beneficial to maintain a connection between the donor eNB and the RN, which uses very few radio resources, in order to enable the RN to switch back to the "normal RN" mode when enough radio resources become available for the backhaul.

The deployment of RNs that can also simultaneously act as home eNBs will not only make the system more flexible by creating alternatives for load sharing and load switching, it also makes the system more robust to failures. That is, when the radio resources in one of the backhaul links of the RN are exhausted, there is still a way to transfer the load via the home eNB interface and vice versa.

A typical usage scenario for a home eNB enabled RN is to use the wireless backhaul connections for RT services with very strict QoS requirements while using the Internet for NRT services and for RT services with more relaxed QoS requirements. This is due to the fact that the operator has full control over the different (wireless) networks available for the backhaul link, but not on the Internet. Notable latency may be expected due to the longer path needed for the packets if the RN is operating as a home eNB for the first two options. For example in the uplink, in the home eNB case the path is UE-RN-GAN-Gateways while for the first and second options (in the home eNB mode), it will be UE-RN-GAN-donor eNB-GAN-Gateways. That is, option 1 and home eNB mode of option 2 are more suitable for NRT services or RT services with relaxed QoS requirements, while the normal relay mode of option 2 (and to some extent, option 3) is more suitable for RT services with strict QoS requirements.

6. Distributed Relaying

When we refer to relaying, especially in the context of relay enhanced LTE, the normal assumption is that there is a one-to-one association between RNs and eNBs (i.e., multiple RNs can be connected through an eNB, but an RN is connected only to one eNB). Though such an architecture, as shown in Figure 2, is a straightforward and simple solution to enable relaying in LTE, it might limit the system performance because the end-to-end performance of relayed UEs will be constrained by the capacity available on the backhaul link between the donor eNB and the core network (i.e., the link that is accessible through the S1 interface). For example, even if there are sufficient radio resources for the relay link, the performance of relayed UEs can degrade if there is congestion

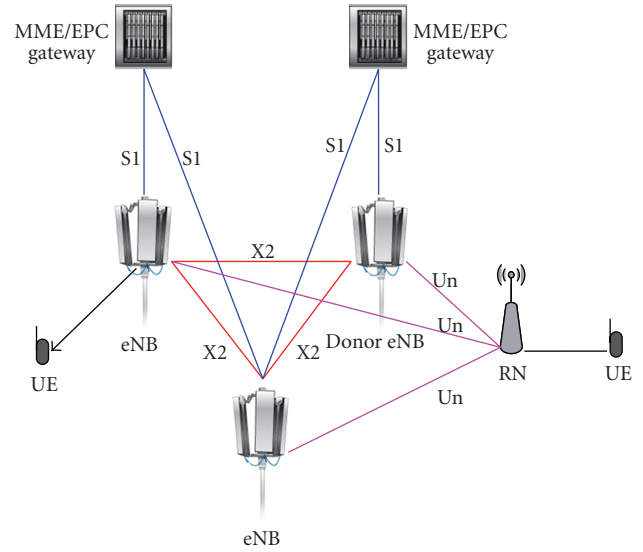


FIGURE 7: Architecture for enabling distributed relaying in LTE.

in the backbone. In practice, S1 links are expensive, and usually operators do not deploy enough capacity to support the maximum cell capacity offered by the air interface.

Apart from the backbone that can turn out to be a bottleneck, we can have insufficient resources on the relay link with the donor eNB while we have a lightly loaded neighbouring cell. In [12], it is proposed that neighbouring cells can communicate their load information via the X2 interface, which will then probably lead to the handover of some of the users to the neighbour cell. However, the S1 links of the two eNBs (assuming they use different S1 links) are not shared; that is, the load sharing is performed by handing over some of the users to the slightly loaded cell. Though handover to the lightly loaded cell is an option, it is not a totally flexible solution as back and forth handover of the relay and all its relayed UEs between eNBs can be an expensive procedure. Not only that, with handover we are only able to use the capacity of just one neighbour cell, instead of the sum of the available capacity in all the neighbouring cells.

In order to enable many-to-many connections between RNs and eNBs, the RNs can be connected to multiple eNBs through the Un interface, or one connection can be kept with the donor eNB and this eNB distributes the data to neighbouring eNBs via the X2 interface. Since the focus of this paper is on the radio access network, rather than the transport network, we will focus only on the first approach.

Figure 7 shows the architecture of a relay enhanced LTE system modified to support multiple Un connections. Originally, the RN is associated only with the donor eNB, and it remains so if the required QoS can be achieved for the relayed UEs. Then, due to congestion on the S1 link and/or unfavourable conditions on the Un radio link, the performance of the relayed UEs starts to degrade. At this point, based on the latest measurement reports by the RN regarding neighbouring eNBs, the donor eNB may contact suitable neighbouring eNBs to find out how much and which

resources they are willing to share in providing additional Un radio links for the RN. These include all the necessary radio network identifiers and radio configuration information for the RN to establish and communicate with and via the relevant neighbouring eNB(s).

Once an agreement is reached between the donor eNBs and its neighbours, the donor eNB may contact a central network controller (i.e., a new functionality introduced in, e.g., the gateway to support SONs) to set up corresponding coordinated S1 links with indicated neighbouring eNBs for the RN and request the RN to establish additional Un radio connection with the concerned eNBs according to the assigned configurations.

The RN will still have only one donor eNB that is responsible for network coordination and control but this donor eNB role can be switched between the different eNBs depending on the resources available in the different cells. The RN will be notified either by the donor eNB or by the new eNB(s) as to which resources it can use to communicate with the new eNB(s).

Thus, in the uplink, the RN from then onwards will send data to a given eNB if the resources used are those assigned for communicating with that eNB. The data is delivered via multiple S1 links to the gateway. The gateway may have to resequence the data arriving from the different eNBs before forwarding them to the destination, similar to the case of handover.

The downlink operation may require the gateway to distribute the data to multiple eNBs. The gateway can be informed which eNBs are connected to the RN and depending on the load of the S1 links of these involved eNBs, the gateway will route the data over the different S1 links. Data belonging to the same bearer may end up being routed via different S1 links, and thus there should be a mechanism on the RN to resequence the data flow. Though this way of data distribution is optimal from the usage of the S1 link, it is suboptimal as it does not consider the load on the relay link of the different eNBs. A periodic reporting of the relay link load of the different eNBs could thus be beneficial for the gateway in order to distribute the load reasonably.

Another way to distribute the data is to let the eNBs and the gateway collaborate to decide which bearers should be delivered through which eNBs, and the gateway routes the downlink data based on this agreement. This is simpler than the fully gateway controlled data distribution described above, as it does not require the resequencing of data that belong to the same bearer. However, it is not as flexible and might lead to suboptimal decisions.

In case multimode RNs are used, the distributed S1 comes handy when the available resources in one network are not enough for the backhaul link and some of the connections have to be transferred to another network (i.e., the RN will have active connections with several eNBs via different network interfaces).

The support of distributed S1 relaying described in this paper is completely transparent to the UEs. However, changes are required in the RN, eNB, and the gateways. For distributing S1 via several X2 links, actually no changes are required at the RN. The most significant change is

the decision mechanism at the eNB, RN, and gateways as to where to route the data, and the resequencing of data arriving via several S1 interfaces at the gateway and data coming via several Un interfaces at the RN. The support of distributed S1 interface will not only make the system more robust to problems related to transport network under dimensioning, but it will also make the system more flexible by creating alternatives for load sharing and load switching.

7. Conclusions

Relaying is expected to play a pivotal role in LTE-Advanced networks, by helping to extend the coverage around cell edges and high shadowing environments and also increasing the capacity in hotspots. Thus, we have proposed a flexible architecture that will enable dynamic relaying in LTE networks, while still maintaining backward compatibility with LTE Release 8 user equipments. The dynamic backhauling configuration proposed in this paper paves the way to flexible, efficient, and self-optimizing multihop cellular networks. Operators do not have to put extensive effort in finding the most optimal locations for placing relay nodes through exhaustive radio planning as optimal eNB-RN associations can be made on the fly. This can lead to big reductions in the planning costs required for enabling relaying in future releases of LTE, enabling even end-users to be able to install relays as easily as WLAN access points. We have also proposed multimode relays that support several network interfaces. This will not only make the system more flexible by creating alternatives for load sharing/switching between different links; it also makes the system more robust to failures. That is, when the resources of one network are exhausted, there is still a possibility to transfer the load fully or partially to other networks, or even using a connection via the Internet, if the RN is enabled to support home eNB functionality. Finally, we have proposed a distributed relaying architecture with many-to-many connections between relay nodes and eNBs, to make the system more robust to problems related to transport network under dimensioning, and also enable load sharing between different cells.

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