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User Multiplexing in Relay Enhanced LTE-Advanced Networks

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Abstract—**The 3rd Generation Partnership Project has recently started the standardization process for LTE-Advanced, as a major evolution step of UTRAN LTE Release 8. One of the key enhancing technologies being studied that may help to fulfill the challenging performance targets of LTE-Advanced networks is radio relaying. This uses relay nodes that act as surrogate base stations for mobile users whose radio links with the base stations are not experiencing good enough conditions. In the downlink, the data that is destined for the relayed users may first have to be multiplexed by the base station, sent over the wireless backhaul link towards the relay node, and de-multiplexed and forwarded to the individual users by the relay node. The reverse process also has to be undertaken in the uplink. In this paper, we present a novel multiplexing scheme which is able to adapt the addressing and bitmapping of user identification to the actual number of users being served by the relay nodes, and thus greatly reduce the multiplexing overhead.**

Keyword: LTE, LTE-Advanced, Relaying, Relay nodes, multiplexing, user multiplexing

I. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) is finalizing the standardization of the Universal Terrestrial Radio Access (UTRA) Long Term Evolution (LTE) Networks, also referred to as LTE Release 8. The work on the next evolution of LTE, known as LTE-Advanced, has already started [1]. The main requirements of LTE-Advanced include high data rate (peak data rates of 1 Gbps in the downlink and 500Mbps in the uplink), low latency (less than 50ms for transition from idle mode to connected mode, and less than 10ms from dormant state to active state), and support for mobility up to 350km/h (up to 500km/h in some specific cases) [1]. LTE-Advanced also requires cell edge users to have a good throughput, as long as guaranteeing that does not create too much system complexity [1]. In order to fulfill these demanding requirements, several technological enhancements are being studied, the main ones being bandwidth extension, improved multiple input multiple output (MIMO) antenna schemes, coordinated transmission and reception between different base stations, and relaying [2][3]. The focus of this paper is on relaying.

The use of radio relaying with the deployment of relay nodes (RN) for coverage extension in cellular networks is not a new concept [4][5][6]. 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 power of cellular networks and enhancing cell capacity and effective throughput. Fig. 1 shows the most typical usage scenarios for relaying.

For the sake of economic viability and reduced standardization impact, LTE-Advanced is required to be as much backward compatible as possible with LTE Release 8, i.e., a RN should be visible to the UE as a normal Release 8 base station (eNB). This is very important because it will allow users to benefit from relaying with their "old" Release 8 terminals. Thus, in the ongoing initial discussions being carried out in 3GPP for the standardization of LTE-Advanced, a Layer 3 (L3) RN that has a similar protocol stack as a Release 8 eNB, at least up to the Packet Data Convergence Protocol (PDCCP) level, is taken as a baseline case [3].

A L3 RN is a surrogate eNB for one or more UEs on behalf of the eNB (referred to as donor eNB or simply DeNB). Whether centralized (where the RN forwards the UE data according to the radio resource allocation assigned by the DeNB) or decentralized (where the RN forwards the UE data by assigning the optimal radio resources within the set of resources it is specified to use by the DeNB), there is a need for multiplexing the data of different UEs in the DeNB and forwarding them to the RN, where the UE data are de-multiplexed and forwarded to the UEs.

In this paper, a dynamic scheme that greatly reduces the multiplexing overhead in the wireless backhaul link between the RN and DeNB is proposed. The rest of the paper is organized as follows. The need for multiplexing and the currently available multiplexing schemes are described in Section II. Section III gives the details of our proposed
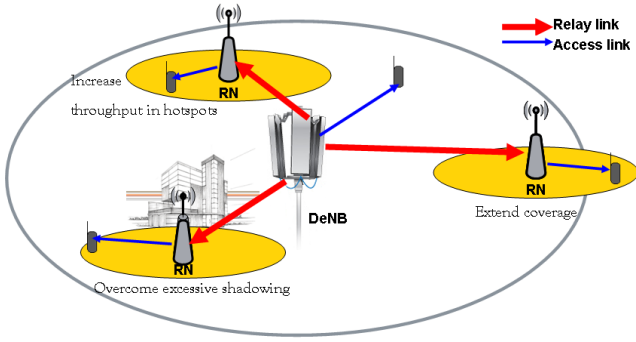
Figure 1: Relaying usage scenarios.

solution and its performance advantages are compared with prior alternatives. The required signaling to enable dynamic multiplexing is discussed in Section IV. Finally, concluding remarks are given in Section V.

II. USER MULTIPLEXING

In LTE Release 8, multiplexing of the data from different UEs is not considered as there are no intermediate nodes, like the RN, between the eNB and the UE. Uplink data arrive at the eNB from individual UEs, in the form of transport blocks (TB), and these transport blocks are mapped one-to-one to the data being sent towards the gateways. A similar process takes place in the downlink.

Fig. 2 illustrates a simplified overview of this process (it applies both to the uplink and downlink). As shown in the figure, data from different bearers arrive at the Radio Link Layer (RLC) in the form of RLC Service Data Units (SDU). An RLC header (RH) is added to the SDUs to form the RLC Protocol Data Unit (PDU). During the formation of the RLC PDUs, segmentation of large SDUs can be performed, and smaller SDU segments can be concatenated together. When these PDUs arrive at the MAC layer, they are concatenated to fit the TB size, which is determined by the number of bits that the UE is scheduled to transmit during the concerned Transmission Time Interval (TTI). During the formation of the TB, data from several bearers that belong to the same UE can be multiplexed.

When we introduce relaying, exactly the same structure can be used in the relay link between the RN and DeNB, if it is possible to send multiple TBs in one TTI between the RN and the DeNB (one TB per TTI per UE of all the relayed UEs). However, one of the requirements of relaying is to be as backward compatible as LTE Release 8. Due to this, it is preferred to make the interface between the RN and DeNB (referred to as the *Un* interface) as similar as possible to the LTE Release 8 interface between an eNB and a UE (referred to as the *Uu* interface). Only one TB per TTI per UE can be sent over the Uu interface, unless we have a MIMO link. Thus, a mechanism is needed to enable the multiplexing of data from different bearers of different UEs into one TB, so that only one TB per TTI has to be sent between the DeNB and RN.

In the WINNER project [5], one of the pioneering research projects where relaying was a core component, user multiplexing is performed by using the ID of each UE whose data is included in the MAC header of the multiplexed MAC PDU.

In mobile WiMAX [6], each connection is identified by a 16 bit connection id (CID) and this is used on the MAC header, and as such it is similar to the WINNER proposal when it comes to UE multiplexing.

A straightforward adaptation of the WINNER and WiMAX multiplexing schemes in LTE will be the use of the 16 bit UE ID known as Cell Radio Network Temporary Identifier (CRNTI) which is used to identify the UEs in each cell. However, this will lead to a large multiplexing overhead.

A backward compatible solution to the user multiplexing solution can be the use of the Logical Channel ID (LCID), which is used in LTE Release 8 to identify different bearers of the same UE. This can potentially be used to identify bearers from a set of different UEs instead, given that a means for multiplexing using this method is defined. However, this field is only 5 bits wide and provides a total of 32 possible addresses. From these 32 addresses, only 9 can be used for identifying a logical channel, while 5 are used for control channels and the remaining part is reserved for future use [7]. Assuming the reserved LCIDs can also be used for relaying, we can have a maximum of 32 - 5 = 27 relayed UEs per RN, each with only one bearer. This is under the assumption that the RN is controlling issues like discontinuous reception (DRX) for which the control LCIDs are reserved for. If these functionalities are controlled by the DeNB, 6 LCIDs (one for data and 5 for control) are needed for each UE. Thus, we can actually have a maximum of only 4 UEs ($\lfloor 27/6 \rfloor$, where $\lfloor x \rfloor$ is an operator that returns the largest integer less than or equal to x).

As it is very likely to have more than one active bearer per UE, the actual number of supported UEs per RN will be much smaller than 27. If we allow each UE to have the maximum number of bearers possible, which is 8 in LTE Release 8, only 3 UEs ($\lfloor 27/8 \rfloor$) can be supported per RN [8]. If issues like DRX are controlled by the DeNB, we can actually support only 2 UEs ($\lfloor 27/13 \rfloor$, as each UE in this case needs 8 LCIDs for data and 5 for control). Thus, the direct use of LCIDs to differentiate UEs as well as bearers is only feasible for a very small number of UEs per RN, even though it is very attractive as the multiplexing could have been performed in exactly the same way as in LTE Release 8, with no additional multiplexing overhead or signaling format changes.

III. DYNAMIC MULTIPLEXING USING VARIABLE ADDRESSING

We propose a dynamic multiplexing scheme that overcomes the problems of the other schemes described in the previous section. This is illustrated in Fig. 3. The main difference from Fig. 2 is the addition of a Transport Block Header (TBH), which gives us the possibility to multiplex data from multiple relayed UEs. A generic format of the TBH is also shown at the bottom of Fig. 3.
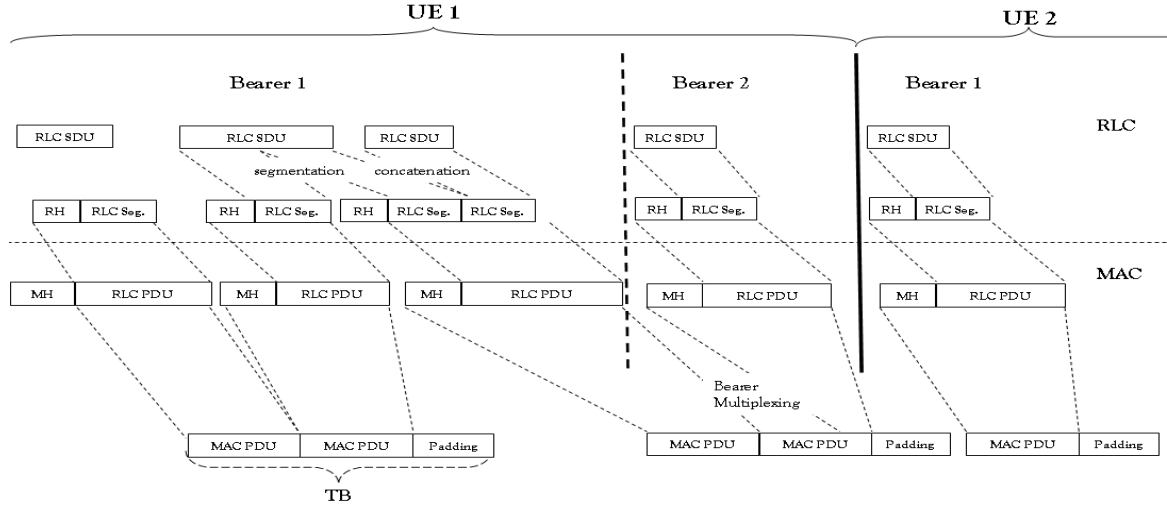
Figure 2: Data flow in the protocol stack in LTE Release 8.

As can be seen in the figure, the TBH contains the fields *ID* and *E*. The ID is an identification of the UE, and the E (Extension) is a one bit field that indicates whether the next block is another header set or data from another UE, i.e., if E=0, MAC PDUs will follow, while if E=1, another header set (ID, E) will follow.

As mentioned in Section II, using a 16 bit UE ID is inefficient due to the large multiplexing overhead. Instead, we propose using a dynamic virtual ID (vID). The length of the vID can be a static or a semi-statically configurable variable and henceforth is referred to as vID Length (vIDL).

The usage/setting of the vIDL that determines the virtual id is as follows:

- The vIDL is set to a default value (*vIDL-default*) when the RN is set up, i.e., unless otherwise modified, the RN will assume the virtual id will be *vIDL-default* bits long.

- A vIDL value of 0 implies that no virtual id is used, and this is equivalent to using the LCID to differentiate bearers regardless of which UE they belong to, as described in Section II. And this allows only unique LCID values per relayed UE.

- A vIDL value of 1 implies that a one bit virtual id is used, and this is equivalent to having a maximum of 2 relayed UEs that can use the same LCID.

- A vIDL value of b implies that a b bit vID is used, and this is equivalent to having a maximum of 2^b relayed UEs that can use the same LCID.

- A vIDL value of 16 is equivalent to using the 16 bit actual UE ID.
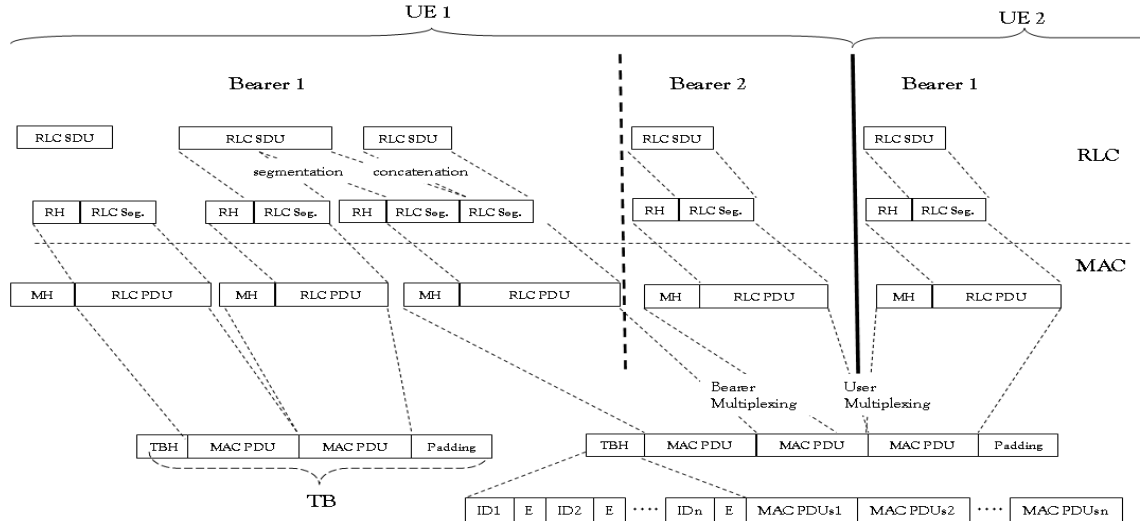

Figure 3: Proposed solution for user multiplexing in LTE-Advanced.

Note that if it is required to treat the RN in the same way as a UE (for configuration/control functionalities such as DRX), we may need a vID for the RN itself. In that case, it will be possible to support only 2^b-1 UEs instead of 2^b with a vIDL value of b.

For the sake of accessing the overhead reduction due to the vID scheme, we consider a simple scenario:

- N users are served by the RN

- there is enough traffic to fill the DeNB-RN backhaul link all the time, and M of the N users are scheduled in a given TTI

- each scheduled user will have an average payload of P bits, where payload in this case refers to MAC header + RLC header + data.

Based on these assumptions, it is straightforward to calculate the multiplexing overhead. For the fixed UE ID case, we will require $(16+1) \cdot M$ bits (the additional 1 bit is for the E fields) for multiplexing the data from M UEs, while with dynamic vIDs, if we have more than one user, we require $(1+\lceil \log_2^N \rceil) \cdot M$ bits, where "$\lceil x \rceil$" is an operator that returns the smallest integer greater than or equal to x.

Thus, the multiplexing overhead for the fixed UE ID case will be:

$$\frac{17M}{17M+(M \cdot P)} = \frac{17}{17+P} \quad (1)$$

while using vIDs (for N >= 2), it will be:

$$\frac{(1+\lceil \log_2^N \rceil) \cdot M}{(1+\lceil \log_2^N \rceil) \cdot M+(M \cdot P)} = \frac{1+\lceil \log_2^N \rceil}{1+\lceil \log_2^N \rceil+P} \quad (2)$$

Fig. 4 depicts the overhead for the two multiplexing schemes, based on the formulations above. As can be seen in the figure, the multiplexing overhead in the case of using fixed UE IDs is independent of the number of UEs being relayed, and can reach as high as 70% with very small payloads. On the other hand, the overhead for the dynamic scheme described here can be as low as 0% (for the case of only one relayed UE), and the worst experienced overhead is lower than that of the fixed UE ID case for all payload sizes.

For most data traffic, the payload is reasonably large, in the range of 1500 bytes, and thus the multiplexing overhead is negligible even for the fixed ID case. However, there are several services like file download and streaming which are mainly unidirectional, and only small sized acknowledgement (ACK) and/or other control packets are sent in the other direction. For example, the size of Transmission control protocol (TCP) ACK packets after header compression ranges between 5 and 15 bytes [9]. As such, even assuming only services like the download of big files, where the packet sizes are large, our dynamic multiplexing scheme can greatly reduce the multiplexing overhead on the uplink.
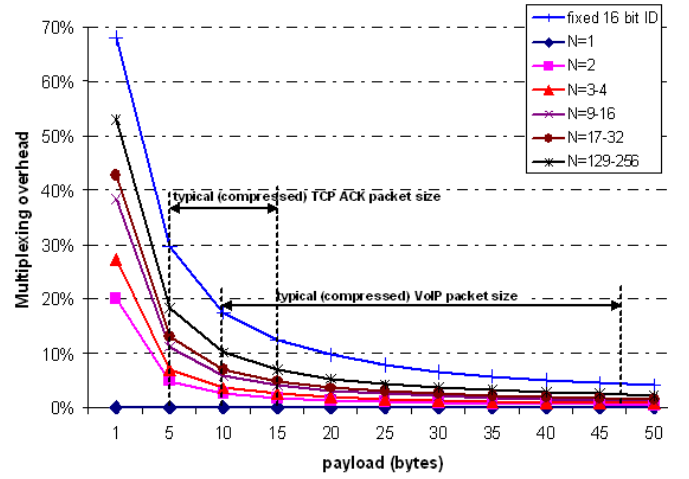

Figure 4: Multiplexing overhead for fixed and dynamic addressing schemes

Voice over IP (VoIP) will be used to transmit voice traffic in LTE-Advanced. The compressed packet size for the most widely used VoIP codecs varies between 10 and 47 bytes [10]. Thus, the multiplexing overhead for a VoIP dominated network can be as high as 18% if fixed UE ID is used, even in the case of only one relayed user. On the other hand, dynamic addressing allows up to 256 relayed users with a maximum multiplexing overhead of only 10%.

IV. ADDRESS SPACE MAINTENANCE

In order to enable the proposed dynamic multiplexing scheme, the Un interface has to be slightly modified (as compared to the Uu interface). However, the Uu interface is unaffected and can remain as in LTE Release 8.

The vID values are assigned per RN, and when a new UE connects to a RN, the vID for the UE can be determined by simply incrementing the maximum value assigned so far. However, there is no need to communicate the individual vID assignments to the RN using separate messages, as the RN can keep track of it itself. A simple implementation will be to have a vID assigned to each UE whenever the UE gets connected to a RN, and both the DeNB and RN update their internal vID counters. This way of UE multiplexing is not only dynamic and saves unnecessary overhead; it is also robust as there is no need to reassign the bearers different LCIDs when there is a handover.

When the current vIDL becomes insufficient to accommodate a new UE, a new value can be set either by sending an explicit message to the RN or implicitly. Since Radio Resource Control (RRC) connections are still controlled /overseen by the DeNB, the vIDL can be communicated within the RRC connection establishment messaging as shown in Fig. 5. As can be seen in the figure, an optional vIDL value field is included in the RRC messages, which can be used to indicate the new vIDL value to the RN in the case where the current vIDL is insufficient to accommodate the new UE.

It might not be required at all to communicate the vIDL to the RN. If the vIDL is set to 0 when 1st relayed UE is connected; vIDL=1 when 2nd UE added; vIDL=2 when 3rd and 4th UEs are added; and so forth, then vIDL and vID can be implicitly known and agreed between the RN and DeNB without a need of configuration as shown in Fig. 5.

When an RRC connection is released, any packets (either in the RN or DeNB) that belong to that UE are flushed, and the vID that was being used for the UE can be recycled and used for upcoming connections. For example, assume the vIDL is 2 and already 4 UEs are being served by the RN. If the connection of the UE with a vID of 1 is released, and a new UE is connected after a while, there is no need to reconfigure the vIDL to 3, as we can simply map the new UE to vID 1.

In order to avoid the vID address space from being filled up in abnormal conditions (such as UEs powering off suddenly without proper RRC connection release), a housekeeping procedure is required. The DeNB can periodically (based on a configurable parameter) check if the connections that have been inactive for a certain duration (a configurable timeout value) are still alive; and recycle the vIDs of the non-responding UEs for future use.

In Section II, it was mentioned that we can directly use LCIDs to multiplex different UEs, but it will allow us only a handful of UEs per RN. However, in conjunction with the dynamic multiplexing scheme, the LCIDs can be used more intelligently, allowing even more UEs per RN than the 2^b limit that is available when using one vID per UE. For example, consider a case where we have a vIDL value of 1, i.e., only two UEs can be identified. Also consider that the two UEs have established two bearers each, using only 4 of the possible $2*27=54$ addresses. So when a third UE gets connected to the RN, in the one vID per UE setting, we have to reconfigure the vIDL value to 2, and assign the new UE a new vID. A more efficient way of implementing this would be to use some of the other 50 unused LCID values for the bearers of the new UE, i.e., the vID field becomes irrelevant if the LCID is used only once. Though this implementation reduces the multiplexing overhead and probability of vIDL reconfiguration, LCID reassignment for existing bearers might be required during handover.
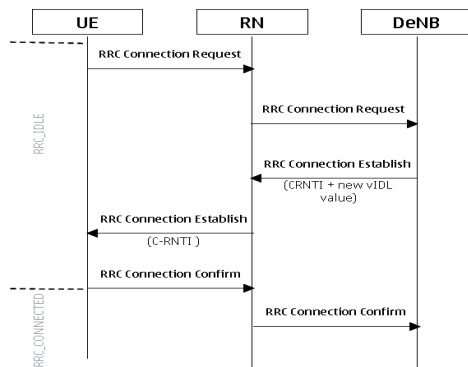

Figure 5: Connection establishment with relays.

V. CONCLUSIONS

The 3GPP has recently started the standardization process for LTE-Advanced, and one of the key technologies that is being studied to fulfill the challenging demands of LTE-Advanced is relaying. Relay nodes act as surrogate base stations for multiple user equipments whose radio links with the base station are not experiencing good conditions. Due to the introduction of the relay nodes between the base station and the UEs, there is a need to multiplex the data that is destined for the relayed users in the wireless backhaul link between the relay node and the base station. This can be done in a rather straightforward fashion, either by reusing LTE Release 8 logical channel IDs to separate the bearers of different users, or by using the 16 bit UE ID in a multiplexing header. However, the former severely limits the number of users that can be served by a RN, while the latter leads to large multiplexing overhead. In this paper, we have proposed a dynamic multiplexing scheme to circumvent these limitations. In this scheme, a variable multiplexing header length is used, where the length of the header is dynamically updated depending on the instantaneous number of relayed UEs and the number of active bearers. It is shown that the scheme performs better than a multiplexing that employs fixed UE IDs, for all practical payload sizes and number of multiplexed users. Also, only minor enhancements have to be made on top of the already standardized LTE Release 8 signaling procedures in order to enable dynamic multiplexing.

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