Relay Backhaul Subframe Allocation in LTE-Advanced for TDD

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ABSTRACT

Relay is a key technology in LTE-Advanced (LTE-A) for both FDD and TDD. A major aspect of relay technology is the backhaul subframe allocation. In this paper, we discuss backhaul subframe allocation for TDD-LTE and analyze all seven downlink-uplink configurations for completeness. The discussion is put in context of latest development in 3GPP physical layer and centered on specifications impact and various design constraints. With the subframe allocation as an example, the article provides insights from wireless industry point of view on how to design TDD-LTE relay system to balance the backward compatibility, the operation cost/complexity and technology advancement.

I. INTRODUCTION

Relay, along with carrier aggregation and advanced MIMO, is one of the key technologies in LTE-A to enhance the system capacity and extend the coverage [1]. LTE-A relay is decode-and-forward relaying, meaning that the relay node (RN) decodes the data from donor cell (DeNB), re-encode and forward to the terminals (UEs). Only two hops are allowed for relaying. The connection between DeNB and RN is called backhaul link or "Un" interface, while the connection between RN and UE is called access link, or "Uu" interface, as seen in Fig. 1. The focus in 3GPP RAN WG1 (Radio Access Network Working Group 1 - Physical layer) is that "Un" and "Uu" share the same frequency band and time division multiplexed, i.e., only one active at any time.

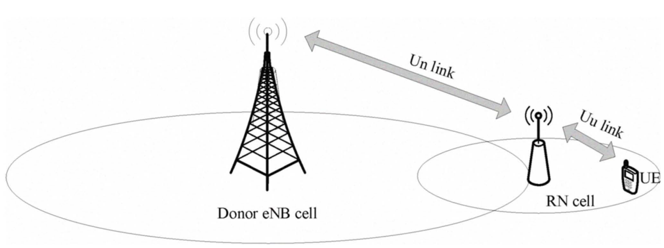

Figure 1. *Backhaul (Un) link and access (Uu) link in a two-hop relay.*

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Type 1 relay, currently in standards development for LTE-A (Release 10) [2], has its own cell ID and appears to a UE as a separate cell distinct from the donor cell. Type 1 relay should support Release 8 UEs for backward compatibility. Release 8 UEs expect continuous CRS transmission from its serving eNB or from type 1 relay node in this context, unless in MBSFN subframes, in order to perform the proper channel estimation and measurement. However, as backhaul link and access link are time-division multiplexed, CRS/data transmission has to be DTXed when type 1 relay node is communicating with DeNB. To create a transmission gap that is also known to relay served UEs, the RN should configure the access subframes to be MBSFN subframes during the backhaul communication with its DeNB, as seen in the right in Fig. 2.

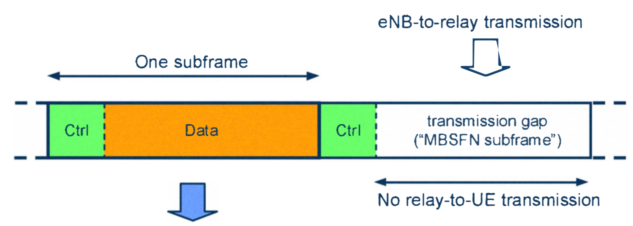

Figure 2. *MBSFN and normal subframes for relay-UE link.*

The first one or two OFDM symbols in an MBSFN subframe contain L1/L2 control signaling for access link. Once the transmission of those symbols is done, the RN switches to reception to hear the control signaling and data from DeNB. Note that RN to UE ("Uu" link) traffic is sent in normal subframes, as seen in the left in Fig. 2. It should be emphasized that MBSFN subframes here are for access downlink, meaning that when an access subframe is configured as MBSFN subframe, there would be downlink control or/and data sent from DeNB to the RN. However, DeNB can use either normal subframe or MBSFN subframe to communicate with RN and co-schedule macro UEs simultaneously. Normal subframes may be used when most macro UEs (co-scheduled with RNs in the same subframe) are Release 8 UEs, and MBSFN subframes may be used when most macro UEs are LTE-A UEs.

In LTE, one radio frame of length 10 ms is equally divided into 10 subframes. For TDD, different uplink and downlink subframes can be configured, resulting in various resource ratios. Note that within a LTE radio frame, FDD subframes #0,

#4, #5 and #9 and TDD subframes #0, #1, #5 and #6 carry important system information, synchronization channels, paging channels, etc. Those subframes should be visible to Release 8 UEs at all times and cannot be configured as MBSFN subframes.

In addition to the MBSFN subframe constraint, backhaul subframe allocation should also consider HARQ timing in both Un link and Uu link. Downlink backhaul subframes should be semi-statically configured and uplink backhaul subframes can be semi-statically configured or implicitly derived from downlink backhaul subframe allocation [1]. Semi-static configuration is usually done via radio resource configuration (RRC) signaling. The implicit allocation is often based on HARQ timing and etc, so that the HARQ conflict between Un link and Uu link is minimized, and the scheduling flexibility on Un and Uu links is maintained.

For FDD, the working assumption is 8ms minimum round trip time (RTT) for backhaul link and to reuse Rel-8 HARQ timing, e.g., synchronous HARQ on Un uplink and 4ms gap between UL grant and UL data transmission [3]. Therefore, the uplink backhaul subframe allocation can be implicitly derived from the backhaul downlink allocation, based on LTE Release 8 uplink HARQ timeline. In TDD, the situation is more complicated due to different HARQ timelines for different DL-UL configurations [4]. It is expected that some changes are needed for HARQ timing in backhaul link in order to maintain the proper HARQ operations in both Un and Uu links.

The paper is organized as follows. Section II discusses the current LTE specifications related to TDD subframe allocations and the design principles. Backhaul subframe allocations are described in Section III for all seven TDD DL-UL configurations. Conclusions are given in Section IV.

II. DESIGN PRINCIPLES

A. Principle 1: strive for reusing Release 8 LTE HARQ timing

To support various resource ratios between downlink and uplink and accommodate different traffic loads on DL/UL, seven DL-UL subframe configurations are defined in TDD-LTE as shown in Table 1 [5]. "S" in Table 1 denotes special subframe whose structure is illustrated in Fig. 3. Those configurations will be reused in access (Uu) links for Release 8 backward compatibility, although not of all of them will be supported in Release 10 [7]. To avoid the interference between DeNB and RN, it is expected that Un link and Uu link would use the same DL-UL subframe configuration. Therefore, the configurations in Table 1 would also be reused in Un link.

HARQ timing depends on the particular location of DL and UL subframe in each DL-UL configuration. HARQ timing for both downlink and uplink traffic and control should be considered, specifically, the relative timing between UL grant (sent over DL) and UL data transmission, the relative timing between DL ACK/NACK and UL data transmission, and the relative timing between DL data transmission and UL ACK/NACK feedback. Principle 1 of backhaul subframe allocation consists of two criteria listed below.

Table 1. *DL-UL subframe configurations in TDD [5]*

DL-UL configuration	Subframe number									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

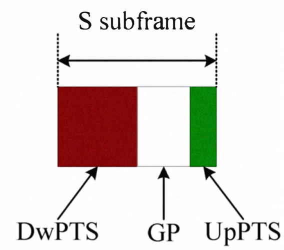

Figure 3. *Structure of S subframe in TDD LTE[5].*

The first criterion considers two timing relationships: 1) UL grant and UL data; 2) DL ACK/NACK and UL data. As defined in Table 2 [5], when an UL grant (transmitted over DL PDCCH) is sent in subframe n, the corresponding UL data should be transmitted in subframe n+k. For example, in DL-UL config#0, if an UL grant is sent in subframe #0, the corresponding PUSCH should be sent in subframe #4.

Table 2. *LTE Release 8 timing relation between UL grant and UL data transmission, k for TDD configurations 0-6[5]*

TDD UL/DL Configuration	DL subframe number *n*									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	4	6				4	6			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

Table 3 [5] specifies that DL ACK/NACK received on PHICH in subframe i shall be associated with the PUSCH transmission in subframe i-k. For example, in DL-UL Config#0, the DL ACK/NACK sent in subframe #0 corresponds to PUSCH transmission in subframe #6 (e.g., mod(0-4, 10)) in previous radio frame. It is noticed that in DL-UL Config. #1, #2, #3, #4, #5, the timing between UL grant and PUSCH complements the timing between DL ACK/NACK and PUSCH by exactly a radio subframe, e.g., the sum of the two k values in Table 2 and Table 3 for a particular DL subframe number is 10. Therefore, in those DL-UL configurations, if backhaul UL grant follows Release 8 time line, it will fit DL ACK/NACK timing of Release 8.

Table 3. *LTE Release 8 Timing relation between DL ACK/NACK and UL data transmission [5]*

TDD UL/DL Configuration	DL subframe number *i*									
	0	1	2	3	4	5	6	7	8	9
0	7	4				7	4			
1		4			6		4			6
2				6					6	
3	6								6	6
4									6	6
5									6	
6	6	4				7	4			6

The second criterion is the timing relationship between DL data and the corresponding UL ACK/NACK. That is when DL transmission occurs in subframe n-k, the corresponding UL ACK/NACK should be transmitted in subframe n. The values of n and k are defined in Table 4 for Release 8 LTE [5]. For example in DL-UL Config #1, the UL ACK/NACK sent in subframe #2 corresponds to PDSCH transmission in subframes #5 or #6 (e.g., mod(2-7,10), or mod(2-6,10)) in previous radio frame.

Table 4.: *k value for UL feedback timing relationship for LTE Release 8 [5]*

DL-UL config	Subframe number n					
	2	**3**	**4**	**7**	**8**	**9**
0	6	-	4	6	-	4
1	7,6	4	-	7,6	4	-
2	8, 7, 4, 6	-	-	8,7,4,6	-	-
3	7, 6, 11	6,5	5,4	-	-	-
4	12, 8, 7, 11	6,5,4,7	-	-	-	-
5	13, 12, 9, 8, 7, 5, 4, 11, 6	-	-	-	-	-
6	7	7	5	7	7	-

It should be pointed out that when a subframe is allocated for Un UL, the RN cannot receive any information, including control signaling, from its served UEs. Therefore, Uu link UL ACK/NACK should be considered when allocating Un UL subframes. Otherwise, Uu downlink HARQ would be affected. This is different from when a subframe is allocated for Un DL. In that case, RN served UEs can still receive UL grant and DL ACK/NACK in MBSFN subframes. In another word, Un DL subframe allocation would not affect UL grant and DL ACK/NACK in Uu link.

B. Principle 2: To minimize HARQ round trip time (RTT)

Sometimes there exist multiple candidates for UL subframe allocations. Among them, we can select those with smaller round trip time, e.g., shorter delay for ACK/NACK feedback, to reduce the latency.

C. Principle 3: To reduce the standards work of specifying new RRC signaling

For Un DL subframe allocation, explicit signaling is required which takes the form of RRC messages. For Un UL, the subframe allocation could be derived from Un DL subframe allocation, to avoid the need to specify another RRC message for UL.

D. Principle 4: RN-RN interference consideration

TDM separation of Un and Uu links implies that the relay node essentially operates in TDD mode when Un and Uu link share the same frequency band. In principle, eNB to eNB type of interference seen in TDD systems would also exist between neighboring RNs when one RN is transmitting and the other RN is in receiving. Simulations in [6] show that RN to RN interference cannot be ignored when the propagation environment is line-of-sight (LOS) and RN-RN distance is small. To avoid excessive RN to RN interference, RN timing is preferred to be globally synchronized and backhaul subframe allocations to be the same at least within the neighboring RNs. Such deployment scenario requires that the choices of backhaul subframe allocations should be limited and typical.

III. SUBFRAME ALLOCATIONS

Based on the design principles discussed in Section 2, we in this section propose some Un subframe allocations for seven DL-UL configurations in TDD.

A. DL-UL Config #0:

Excluding subframes {0, 1, 5, 6}, no other subframe can be configured as MBSFN subframe in this configuration. So we either do not support Config #0 for relay, or use S subframe for DL backhaul transmission as illustrated in Fig. 4. From Fig. 3 it is seen that only portion of S subframe, e.g., DwPTS, can be used for DL transmission, which means limited DL capacity in S subframe if DwPTS is reused as defined in Release 8. Alternatively, DwPTS may be extended to the GP region to improve DL capacity, albeit with the reduced coverage and increased interference.

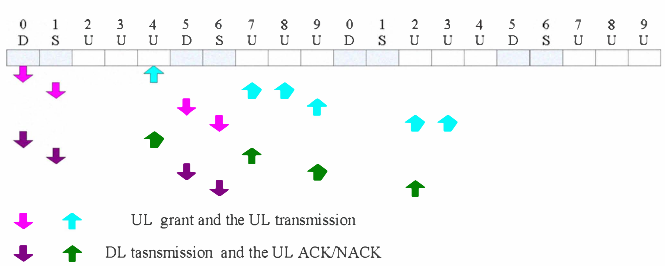

Figure 4. *Un subframe allocation for DL-UL Config #0*

Note that the UL grant for PUSCH in subframe #7 and #8 is transmitted in S subframe #1. Therefore, if S subframe #1 is for DL backhaul, subframes #7 and #8 can be allocated for UL backhaul. Here we can further rule out subframe #8 which has long HARQ RTT and causes excessive delay. In comparison, the HARQ RTT for subframe #7 is much shorter. Checking Table 4, we find that DL/UL pair {1, 7} also fits the timing between DL transmission and UL ACK/NACK.

Same principle is applied when S subframe #6 is used for DL backhaul. So for DL-UL Config #0, two pairs of DL/UL backhaul subframes can be allocated: {1, 7} and {6, 2}. Note that considering the major standards work expected for transmitting DL data over S subframes, RAN WG1 decided not to support DL-UL Config #0 in relay for Release 10 LTE [7].

B. DL-UL Config #1:

Ignoring S subframes, it is seen that only subframes #4 and #9 can be allocated for backhaul downlink. Release 8 HARQ timing relations can be reused without any changes. Fig. 5 shows symmetric DL/UL backhaul subframe allocations. If #4 is allocated for DL Un, subframe #8 would be allocated for UL Un link since the ACK/NACK feedback of DL transmission in subframe #4 is transmitted in subframe #8. In addition, the UL grant corresponding to subframe #8 UL transmission is sent in subframe #4. Similar timing relationship is observed in subframes #9 and #3. Therefore, for symmetric allocation, we can have DL/UL subframe pairs {4, 8} and {9, 3} if S subframes are not used. For asymmetric allocation, we can have {4, 9, 3} or {4, 9, 8}

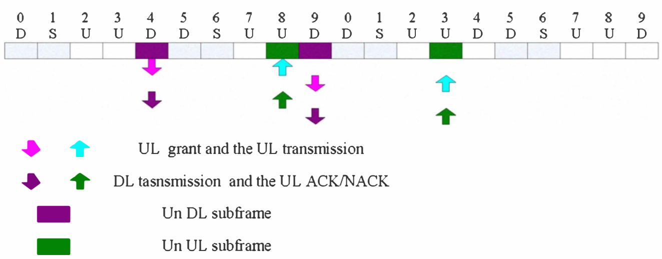

Figure 5. *Un subframe allocation for DL-UL Config #1*

C. DL-UL Config #2:

Possible backhaul DL/UL subframe pairs for DL-UL Config #2 are illustrated in Fig. 6. Ignoring S subframes, there are only two UL subframes, one for Uu link and the other for Un link. If subframe #2 is allocated for Un UL, #8 can be allocated for Un DL, which fits the timing relations in Table 2 and Table 3. Similarly, subframes #3 and #7 can be allocated for Un DL and Un UL, respectively.

The above backhaul subframe allocation can cause minor impact on Uu HARQ operation. For example, according to Table 4, when subframe #2 is allocated for Un UL, no UL ACK/NACK can be received by RN on access link that corresponds to Uu link DL data transmission in subframes #5 and #6. Possible solutions include: 1) not to schedule Uu DL transmission in subframes #5 and #6, which causes resource waste; 2) to use S subframe for Un UL transmission that requires major changes in standards; 3) to enable ACK/NACK repetitions which introduce more delays. For example, if subframe #2 is allocated for Un UL, Uu UL ACK/NACK corresponding to DL transmission in subframe #5 and #6 can be received in subframe #7 when ACK/NACK repetition is configured, resulting in the minimum feedback delays of 12 and 11 ms, respectively.

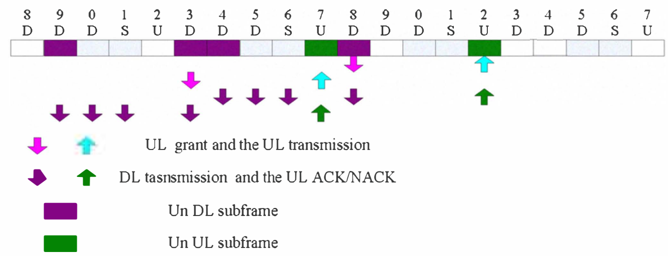

Figure 6. *Un subframe allocation for DL-UL Config #2*

D. DL-UL Config #3:

In this DL-UL configuration, no Un subframe sets could be defined if Rel-8 HARQ timings are strictly followed. Therefore, some HARQ timings in Un need to be redefined to maintain UL ACK/NACK feedback timing in Table 4 to minimize the impact of Un subframe allocation on Uu link HARQ.

For example, corresponding to UL transmission in subframe #3, DL ACK/NACK in Un link can be changed from subframe #9 to subframe #8 or #7. Hence, we can get DL/UL subframe pair for backhaul {7, 8, 3} as shown in Fig. 7.

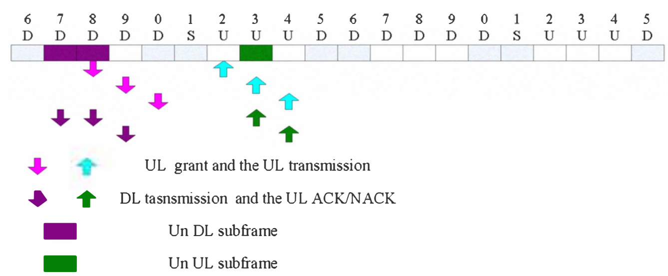

Figure 7. *Un subframe allocation for DL-UL Config #3*

E. DL-UL Config #4:

In this DL-UL configuration, ignoring S subframes, only subframes #2 and #3 are for UL. To minimize the impact on Uu uplink ACK/NACK, we can allocate subframe #3 for UL Un subframe since it only affects Uu DL transmission in subframe #6, otherwise, subframes #0, 1, and 5 would all be affected. According to Release 8 HARQ timing, subframe #9 should then be allocated for Un downlink. Note that the feedback for DL transmissions in subframes #7 and #8 are also transmitted in subframe #3. Therefore, subframes #7 and #8 cannot be used for Uu link, e.g., UL feedback would be lost. To resolve this, subframes #7 and #8 can be allocated for DL Un link and the backhaul DL/UL pairing would be {7, 8, 9, 3} as shown in Fig. 8. Another solution is ACK/NACK repetition which would incur excessive delay especially in DL-UL Config #4 with limited UL subframes.

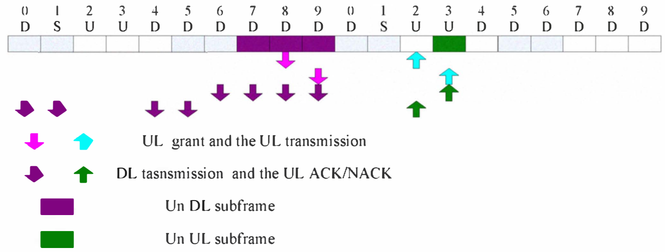

Figure 8. *Un subframe allocation for DL-UL Config #4*

F. DL-UL Config #5:

Excluding S subframes, there is only one UL subframe in DL-UL Config #5 as seen in Fig. 9, meaning that S subframe #1 has to be used for UL backhaul transmission. Significant standards work is needed to re-define S subframe #1 for backhaul uplink since S subframes in Release 8 only carry RACH preamble and SRS on uplink. To avoid excessive HARQ RTT, subframe #7 can be allocated for DL Un and we get DL/UL subframe pair of {7, 1}.

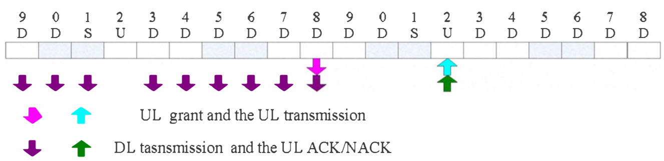

Figure 9. *Un subframe allocation for DL-UL Config #5*

Due to the significant standards work required for UL data transmission over S subframes, DL-UL Config #5 will not be supported in Release 10 relay [7].

G. DL-UL Config #6:

Ignoring S subframe, only subframe #9 can be allocated for Un DL in this configuration. In Table 4, the corresponding UL ACK/NACK should be sent in subframe #4. Therefore, #4 can be configured for Un UL and we get the backhaul subframe pair {9, 4}. Note that DL ACK/NACK for Un UL transmission in subframe #4 needs to be moved from subframe #0 to #9 as shown in Fig. 10

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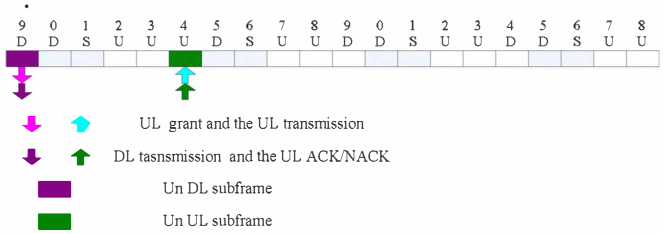

Figure 10. *UL subframe allocation DL-UL Config #6*

Un subframe allocations discussed so far are based on Release 8 HARQ timing relationship specified in Tables 2-4, with small modifications in Table 3 for some DL/UL configurations. In some sense, the allocation of Un UL is implicit if Un DL backhaul subframe allocation is given. For the simplicity of relay operation particularly in TDD, a subset of Un subframe allocations can be defined which is chosen from the bigger pool of implicit allocations. Such subset should be typical and can be specified in the standards, and possibly signaled explicitly.

IV. Conclusions

In this paper, we began with the background introduction of standards development in 3GPP for LTE-A. Major discussion was spent on relay backhaul subframe allocation for TDD LTE-A. Some design principles were provided to help readers to understand the issues and design constraints related to HARQ timing in both backhaul and access links, together with the requirement of LTE Release 8 backward compatibility. For completeness, all seven DL/UL TDD configurations were analyzed where in each configuration we suggested at least one subframe pair for DL and UL backhaul allocation. The paper can be used as an example of how to design or enhance TDD system with consideration of backward compatibility, standards work, performance and system complexity.

References

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