Evolution of Reference Signals for LTE-Advanced Systems

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ABSTRACT

3GPP LTE Release 10 standards (also known as LTE-Advanced) adopted some of the *state-of-the-art* radio access technologies that include carrier aggregation, eight-layer downlink spatial multiplexing, and four-layer uplink spatial multiplexing. For facilitating these enhancements, reference signals have significantly evolved in LTE-Advanced. This article examines underlying design principles of the LTE-Advanced reference signals. Specifically, newly introduced dedicated demodulation reference signals and channel state information reference signals for downlink and improvements of demodulation reference signals and sounding reference signals in uplink are discussed.

INTRODUCTION

The Third Generation Partnership Project (3GPP) Evolved Universal Terrestrial Radio Access (E-UTRA) Release 10 standards (i.e., Long Term Evolution [LTE]-Advanced) are evolved from the Release 8 and 9 standards to support the International Mobile Telecommunications (IMT)-Advanced peak data rate targets of 100 Mb/s for high mobility and 1 Gb/s for low mobility. Furthermore, LTE-Advanced systems target support for downlink peak spectral efficiency of 30 b/s/Hz and uplink peak spectral efficiency of 15 b/s/Hz, and support for approximately 1.5× improved cell average and cell edge spectral efficiency over Release 8 and 9 standards [1]. In order to achieve these peak data rate and peak spectral efficiency targets, LTE-Advanced introduced carrier aggregation, eight-layer downlink, and four-layer uplink multiple-input multiple-output (MIMO) spatial multiplexing. On the other hand, to achieve the cell-average and cell-edge spectral efficiency targets, enhanced intercell interference coordination (e-ICIC), enhanced single-user (SU-) and multi-user (MU-) MIMO, and clustered discrete Fourier transform (DFT) spread orthogonal frequency-division multiplexing (OFDM) for uplink are introduced. This article presents technology advancements of reference signals to efficiently support the enhanced transmission schemes newly introduced in LTE-Advanced.

LTE systems make use of pilot signals, known as reference signals (RS) for downlink and uplink channel estimation. Downlink RS are provided for channel state information (CSI) measurement for feedback and channel estimation for demodulation. The Release 8 LTE design of downlink RS primarily relied on a set of cell-specific reference signals (CRS) that can be used for both purposes. The CRS are wideband pilot signals transmitted across the downlink system bandwidth in every subframe and are defined for up to four antenna ports[1] (APs). To support 8-layer spatial multiplexing in LTE Release 10, low duty-cycle wideband reference signals, called CSI reference signals (CSI-RS) are introduced for CSI measurement. Furthermore, a new set of user equipment (UE)-specific RS (UE-RS) is defined to enable channel estimation for demodulation instead of introducing 4 additional CRS. This Release-10 design is beneficial to efficiently support high rank transmissions because UE-RS requiring higher overhead is present only in those physical resource blocks in which higher rank is used. On the other hand, uplink RS are provided for uplink CSI measurement (also called uplink channel sounding), link adaptation, timing estimation, power control, and channel estimation for demodulation. LTE Release 8 defines two types of uplink RS: demodulation RS (DMRS) for demodulation and sounding RS (SRS) for the other purposes. DMRS are sent together with uplink data, whereas SRS are periodically transmitted from each UE unit according to a radio resource con-

[1] *In 3GPP E-UTRA systems, each antenna port is characterized by a reference signal, and is not necessarily a physical antenna.*

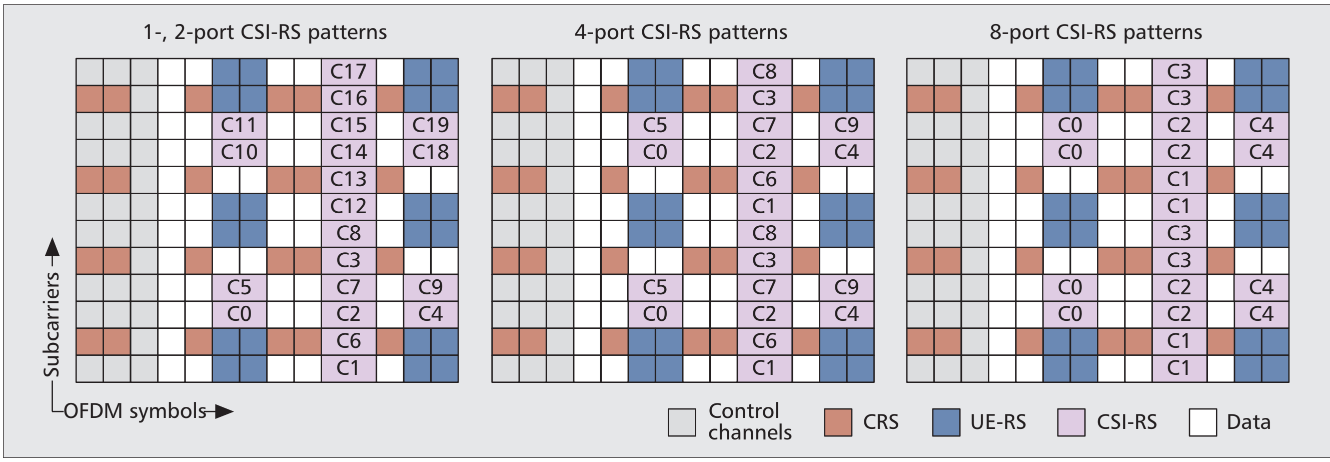


Figure 1. *CSI-RS mapping patterns for 1-, 2-, 4-, and 8-port CSI-RS.*

trol (RRC) layer configuration. To support channel estimation on multiple APs for uplink spatial multiplexing and to more flexibly support uplink MU-MIMO, Release-10 LTE-Advanced introduces further enhancements to the uplink RS. These enhancements include application of orthogonal cover codes (OCC) that improve the orthogonality of multiple DMRS across APs and multiple UE units, and introduction of aperiodic SRS transmission so that base stations (or eNodeBs) can more efficiently manage SRS resources across the increased number of UE units and/or APs in LTE-Advanced systems.

This article is organized as follows. We describe the motivation, design choices, and structure of the new downlink RS covering CSI-RS and UE-RS, and discuss the new uplink RS. Some concluding remarks are provided.

Evolution of Downlink Reference Signals

Channel-State-Information Reference Signals

CSI-RS are reference signals transmitted from eNodeB APs in order for UE to measure downlink CSI. The introduction of CSI-RS in LTE-Advanced systems allows reduced RS overhead and flexible configurations of multicell RS measurements.

CSI-RS Patterns — A CSI-RS supports up to eight APs and is transmitted in a wideband manner. Figure 1 shows CSI-RS mapping patterns in a pair of physical resource blocks[2] (PRBs) for normal cyclic prefix (CP) subframes.

Depending on the number of CSI-RS APs, there are multiple reuse patterns on different locations which share a common base pattern. In the case of 1-, 2-, 4-, and 8-AP CSI-RS, there are 20, 20, 10, and 5 reuse patterns, respectively, allowing different cells to utilize different reuse patterns to avoid mutual CSI-RS collision. In addition, the base patterns for different numbers of CSI-RS APs have a nested structure, allowing for simpler CSI-RS transmitter and receiver implementation.

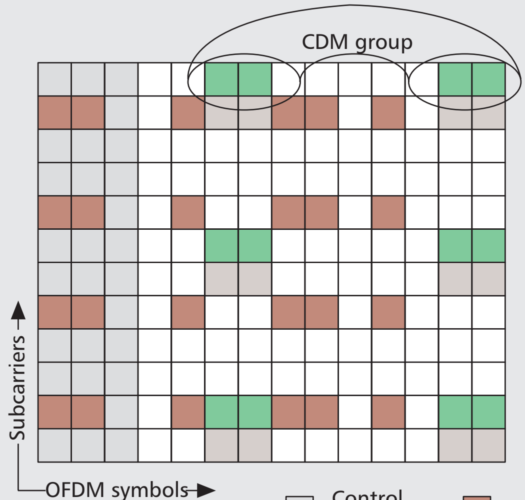
Each AP's CSI-RS are spread over two time-consecutive resource elements[3] (REs) such that two different CSI-RS are code-division multiplexed (CDM'ed) in the two REs. One of the major benefits of CDM as compared to other multiplexing schemes such as FDM is that CDM can balance transmission power across APs in the frequency domain.

The CSI-RS density is closely related to the channel estimation accuracy. In general, larger CSI-RS density may provide better CSI measurement accuracy while reducing downlink resource utilization. Therefore, adequate CSI-RS density, which occupies minimum downlink resources while providing reasonable CSI measurement accuracy, is desirable. Since CSI-RS is only used for downlink channel measurement and feedback reporting, granularity is coarse due to feedback overhead; the system performance is relatively insensitive to the channel measurement accuracy as compared to that for UE-RS. Therefore, a low-overhead CSI-RS transmitted only once every 5, 10, 20, 40, or 80 ms is employed in LTE-Advanced. A typical transmission of CSI-RS, which may consist of 4 APs with periodicity of 10 ms, would only require an overhead equivalent to 0.2 percent of the entire time and frequency resources. The low overhead is achieved by allocating a single RE per PRB pair per CSI-RS AP except when the CSI-RS has only one AP, in which case two REs are allocated per PRB pair. During the evaluation phase of CSI-RS in 3GPP [2, 3], it was observed that better measurement accuracy by having a higher density than 1 did not improve the performance of downlink transmission in a realistic environment.

Performance Impact of CSI-RS on Legacy UE — When CSI-RS are transmitted in PRBs assigned for a legacy UE, the CSI-RS replace legacy data symbols on CSI-RS REs. Because a legacy UE has no knowledge of CSI-RS, its receiver would consider CSI-RS as valid data symbols in such a PRB. This leads to demodulation performance degradation as the legacy UE is not only losing coded information but is also being interfered by the CSI-RS in its decoding process. The adverse impact on the legacy UE becomes more serious as the number of CSI-RS

[2] *A pair of PRBs is the minimum resource allocation size in 3GPP E-UTRA systems. Each PRB consists of 12 consecutive subcarriers in the frequency domain and x consecutive OFDM symbols in the time domain, where x = 6 for extended cyclic prefix subframes and x = 7 for normal cyclic prefix subframes. In this article, we consider only normal cyclic prefix subframes for simplicity of presentation.*

[3] *A resource element (or an RE) is a unit element of the OFDM time-frequency grid in 3GPP E-UTRA systems, which is uniquely identified by a subcarrier index and an OFDM symbol index.*



Antenna port	CDM group	Spreading code 1	Spreading code 2
7	1	[+1+1+1+1]	[+1+1+1+1]
8	1	[+1–1+1–1]	[–1+1–1+1]
9	2	[+1+1+1+1]	[+1+1+1+1]
10	2	[+1–1+1–1]	[–1+1–1+1]
11	1	[+1+1–1–1]	[–1–1+1+1]
12	2	[–1–1+1+1]	[+1+1–1–1]
13	1	[+1–1–1+1]	[–1+1+1–1]
14	2	[–1+1+1–1]	[+1–1–1+1]

Figure 2. *UE-RS pattern and spreading sequences.*

APs grows larger [2, 3]. To mitigate system performance loss arising from this side effect, an eNodeB may allocate additional PRBs in transmitting a transport block, or assign a reduced modulation and coding rate to such legacy UE. The eNodeB may also choose to avoid scheduling legacy UE in the subframe containing CSI-RS.

Data Resource Element Muting for Intercell CSI Measurement — Although different CSI-RS patterns are likely to be used in neighboring cells to minimize mutual CSI-RS collision, neighbor cells' downlink data signals may still significantly interfere with CSI-RS received at cell edge UE in a heavily loaded network in interference-limited scenarios. In addition, accurate CSI measurement for neighbor cells is also required for better support of coordinated multipoint (CoMP) transmissions in future releases. To cope with the interference problems and to facilitate CSI measurement of neighbor cells for CoMP, LTE-Advanced Release 10 supports *data RE muting*, whereby data REs colliding with CSI-RS in a neighbor cell are transmitted with zero transmission power (i.e., muted REs). For LTE-Advanced UE, the eNodeB applies code rate matching around the muted REs so that LTE-Advanced UE is able to decode data accordingly.

UE-Specific Reference Signals

UE-RS are precoded pilots used for data demodulation. They are transmitted only on the PRBs allocated for each UE's data, and are precoded with the same precoder used for the data.

There are several advantages of UE-RS-based operations over CRS-based operations. The UE-RS pilot overhead depends only on the transmission rank (or the number of assigned transmission layers or streams) and is decoupled from the maximum transmission rank supported by the system. In addition, channel estimation for demodulation can be performed per layer, which is desirable for CoMP and heterogeneous networks. For example, in CoMP joint transmission, where multiple transmission points jointly beamform to transmit to UE, the UE does not need to know which transmission points are involved in the joint transmissions; hence, the related information does not need to be signaled. Furthermore, UE-RS-based operation facilitates non-codebook-based frequency-selective precoding, which can improve downlink throughput, especially in MU-MIMO and CoMP transmissions. For CRS-based transmissions, a selected precoding matrix (or matrices) has to be signaled to UE so that the UE can calculate the precoded channels utilizing the channel estimates obtained from CRS. However, for UE-RS-based transmissions, frequency-selective precoders can be selected across the allocated PRBs not being constrained by a fixed codebook, since UE can estimate precoded channels per PRB directly from UE-RS. Finally, with UE-RS, UE can obtain more accurate interference estimates in partial loading scenarios. UE-RS always collide with either data signals or UE-RS of neighboring transmission points, which are present only when data signals are transmitted; however, in CRS-based operations, CRS may collide with CRS of neighboring transmission points, which makes interference estimates obtained from CRS incorrect when data signals are not transmitted.

UE-RS Pattern and Spreading Sequences — The UE-RS pattern is shown in Fig. 2. It consists of two CDM groups each of which can multiplex up to 4 UE-RS (for 4 APs). The second CDM group is used only for rank > 2; hence, the pilot density is 12 REs per PRB pair for ranks 1 and 2, and 24 REs per PRB pair for rank > 2. The pattern provides three looks of each layer's channels in frequency in order to support reliable channel estimation with delay spread up to 5 μs.

For r-layer data transmissions APs 7 to $6 + r$ are used, while a single-layer allocation using AP 8 to UE is also allowed to facilitate MU-MIMO operation. The mapping of APs to CDM groups and the spreading codes is shown on the right side of Fig. 2. The spreading codes are selected such that for up to four-layer transmissions, the CDM-multiplexed pilots can be orthogonalized by despreading over two contiguous REs in time. Thus, this can provide two looks at each layer's channels in time, which is beneficial to estimate channels at moderate to high Doppler. For more than four-layer transmissions, the pilots can only be orthogonalized by using all four REs in time on the same subcarrier where some of the REs are not contiguous, and hence the pilots remain orthogonal only for low speeds. However, this is not a significant restriction as MIMO with more than four layers is likely to be used only at very low Doppler. The spreading code alternates in frequency between spreading codes 1 and 2. This alternating pattern helps reduce the peak-to-average-power ratio, for example, when the same precoding matrix is used across all the PRBs in the system bandwidth. It also helps mitigate the impact of residual interlayer interference remaining after CDM despreading at high Doppler on the channel estimate.

Furthermore, a cell-ID-based scrambling sequence is applied to UE-RS to ensure that a UE unit is able to distinguish its UE-RS from the UE-RS of neighboring base stations. For APs 7 and 8, two scrambling sequences are defined for each cell ID. This allows MU-MIMO multiplexing of up to four UE units where UE-RS with the same scrambling sequence are orthogonally multiplexed, while UE-RS with different scrambling sequences are non-orthogonally multiplexed.

Control Signaling for UE-RS Allocation — For each UE unit's downlink receptions, the number of transmission layers (i.e., the transmission rank) and corresponding UE-RS AP numbers are dynamically signaled. When rank > 2 is signaled, a UE unit's demodulator can safely assume that there are no co-scheduled UE units in the UE's allocated PRBs as the LTE-Advanced system does not allow more than two orthogonal UE-RS multiplexing for MU-MIMO. On the other hand, when either rank 1 or rank 2 is signaled, it is possible that the UE's signal is multiplexed with other UE units' signals in some of the allocated PRBs. While for optimizing performance of an MU-MIMO/SU-MIMO receiver information about co-scheduled UEs in each of the allocated PRB is essential, LTE-Advanced has not defined signaling for such information, partly because the signaling overhead is significantly high when different sets of UE are multiplexed in different PRBs. Nevertheless, MU-MIMO multiplexed UE can blindly detect co-scheduled UE in each allocated PRB by measuring power on UE-RS of the APs and scrambling sequences not allocated to the MU-MIMO UE itself.

Traffic to Pilot Power Ratio — The traffic to pilot power ratio for UE-RS is fixed to 0 dB for ranks 1 and 2, and 3 dB for rank > 2, in which case the average UE-RS power per RE is the same as the average data signal power per RE. For MU-MIMO operation, such a condition helps to ensure that interference measured on UE-RS REs is same as that seen on data REs.

PRB Bundling — When an eNodeB can estimate the downlink channel per PRB (e.g., from uplink sounding using channel reciprocity), the eNodeB may want to choose frequency-selective precoders in different PRBs to improve the throughput. However, when an eNodeB's CSI for a UE is obtained only from precoder matrix information (PMI) and rank information (RI) feedback, the eNodeB is forced to use the same precoder across multiple consecutive PRBs in the frequency domain as feedback granularity is not a single PRB. To facilitate achieving the frequency-selective precoding gains when per-PRB CSI is available, and at the same time improve channel estimates at the UE when only PMI/RI feedback is available, the LTE-Advanced specifies that UE configured with PMI/RI feedback may assume that the same precoder is applied to each of the PRBs belonging to a precoding resource block group (PRG), whereas UE not configured with PMI/RI feedback should assume that different precoders are applied in different PRBs for UE-RS channel estimation.

Evolution of Uplink Reference Signals

In this section, we describe the basic structure of uplink DMRS and SRS. The limitations of the Release 8 design are analyzed, and the design choices for Release 10 enhancements are presented.

Evolution of Demodulation Reference Signals

Required Property for LTE-Advanced DM RS — For Release 8 LTE uplink DMRS, extended Zadoff-Chu (ZC) sequences are adopted [4] because the ZC sequences ensure low peak-to-average-power ratio (PAPR) and at the same time provide mechanisms to orthogonalize multiple DMRS transmitted in MIMO spatial multiplexing schemes. Using different cyclic time shifts (CS) of a root ZC sequence, multiple users' DMRS transmitting to the same eNodeB can be orthogonally CDM'ed as long as the multiple DMRS are transmitted in the same set of PRBs.

In LTE-Advanced, SU-MIMO with up to four-layer spatial multiplexing is supported. Although the DMRS corresponding to different layers can theoretically be orthogonalized by the Release-8 LTE mechanism of assigning different CS to each layer, the CS orthogonality can be broken in case of high delay spread. In addition, the CS orthogonality is guaranteed only when the root ZC sequences are identical in waveform and length, which implies that the time-frequency allocations of MU-MIMO-multiplexed UE should be identical. Uplink DMRS in LTE-Advanced are designed to overcome these drawbacks while maintaining backward compatibility.

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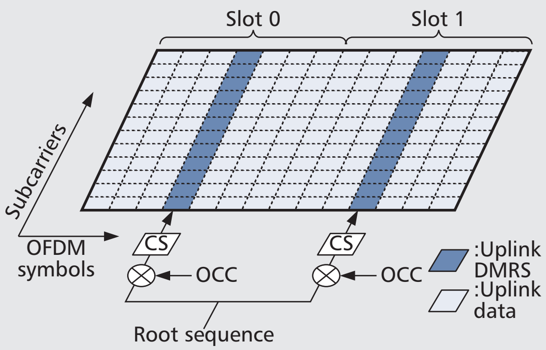
Structure of LTE-Advanced Uplink DMRS — In LTE and LTE-Advanced, two single-carrier frequency-division multiple access (SC-FDMA) symbols are configured for DMRS in a subframe within the allocated time-frequency resources, as shown in Fig. 3a. Each uplink RS sequence is given by



(a)

Signaling bit	Cyclic shift (α)				Cyclic shift (α)			
	λ=0	λ=1	λ=2	λ=3	λ=0	λ=1	λ=2	λ=3
000	0	6	9	3	[+1+1]	[+1+1]	[+1–1]	[+1–1]
001	6	0	3	9	[+1–1]	[+1–1]	[+1+1]	[+1+1]
010	3	9	6	0	[+1–1]	[+1–1]	[+1+1]	[+1+1]
011	4	10	7	1	[+1+1]	[+1+1]	[+1+1]	[+1+1]
100	2	8	5	1	[+1+1]	[+1+1]	[+1+1]	[+1+1]
101	8	2	11	5	[+1–1]	[+1–1]	[+1–1]	[+1–1]
110	10	4	1	7	[+1–1]	[+1–1]	[+1–1]	[+1–1]
111	9	3	0	6	[+1+1]	[+1+1]	[+1–1]	[+1–1]

† w denotes OCCs applies for first and second slot

‡ λ denotes layer index for SU-MMO.
And CS value(s) for λ=[0..x-1] is used when rank-X data channel transmission is indicated

(b)

Figure 3. *Uplink subframe structure and mapping table of CS and OCC: a) uplink subframe structure; b) mapping table of CS and OCC.*

$$r^{(\alpha)}(n) = we^{j\alpha n/12}\bar{r}(n) \qquad (1)$$

in the frequency domain, where n is the subcarrier index, $\bar{r}(n)$ is the root ZC sequence generated by an extended ZC sequence, and α is the CS value [4]. LTE Release-10 employs codebook-based precoding for uplink SU-MIMO data transmissions, and the same precoding mechanism is applied for uplink DMRS transmissions. As such, a receiver can directly estimate the spatially combined precoded channel. Note that DMRS are split in the same manner as data when clustered DFT spread OFDM is used.

An eNodeB can choose root ZC sequences for the RS by considering the auto- and cross-correlations among neighboring eNodeBs. However, such deployment planning is not always straightforward for cellular operators. Hence, a root ZC sequence randomization mechanism called sequence hopping and sequence group hopping (SGH) [5] is available depending on each operator's choice, where the root ZC sequence varies in every slot if SGH is enabled. The scalar value of w (i.e., +1 or –1) in Eq. 1 is a newly introduced feature called OCC, which is used to spread the RS sequence into two OFDM symbols. The motivation to introduce OCC is to efficiently support SU- and MU-MIMO.

Enhancements Aimed at Improving SU-MIMO Performance — In SU-MIMO operation in which a UE transmits multiple layers simultaneously, multiple DMRS can be orthogonally multiplexed by assigning different CS for the multiple layers. However, the CS orthogonality may be broken when the delay spread is high, because the impulse response of each layer leaks into the correlation window of another layer in the time domain as the CS separation becomes smaller. To further separate the multiple DMRS, OCCs are introduced in LTE-Advanced. As shown in Fig. 3b, different OCCs are applied for higher-numbered layers (i.e., λ ≥ 3) and lower-numbered layers (i.e., λ ≥ 2), so the multiple RS for the higher rank transmission (i.e., rank ≥ 3) are still well orthogonalized even if CS separation is small. Although the orthogonality by the OCCs may also be broken by high Doppler shift, the effect is minimal because higher rank transmission is mainly used for low-mobility UE.

Enhancements Aimed at Improving MU-MIMO Performance — From the viewpoint of DMRS orthogonality, MU-MIMO schemes are categorized into two types, *identical-band MU-MIMO* and *non-identical-band MU-MIMO*, and OCC is used to realize non-identical-band MU-MIMO. Identical-band MU-MIMO is a scheme in which the frequency band allocations for MU-MIMO UE are identical, and DMRS orthogonality can be achieved by assigning different CS. Although this scheme is Release 8 compatible and hence can be used for multiplexing Release 8 and Release 10 UE, the scheduling restriction may negatively impact on the uplink system throughput performance. On the other hand, non-identical-band MU-MIMO is a scheme in which the frequency band allocations for MU-MIMO UE are not identical. Although this improves frequency scheduling flexibility and hence may improve the uplink system throughput [6], it implies that the DMRS root ZC sequences for the two slots of a subframe should be the same to utilize OCC [7].

Signaling Design — In LTE-Advanced, CS and OCC are assigned to a UE unit via physical layer signaling. To reduce downlink signaling overhead, a 3-bit field is used to signal a combination of the CS and OCC, as shown in Fig. 3b. This 3-bit field is designed based on the following aspects.

Maximum separation of CS space for SU-MIMO: The CS values are chosen to maximize the minimum CS separation considering both SU-/MU-MIMO. The separation value is determined considering maximum four-layer multiplexing irrespective of transmission rank. Thus, the CS indication for the first layer implicitly determines the CS for all other layers.

OCC to achieve further orthogonality for SU-MIMO: OCCs for SU-MIMO are used to achieve further orthogonality to maximize the RS separation. Along with the CS assignment rule above, different OCCs can be assigned for layer {0, 1} and layer {2, 3}. This can be turned

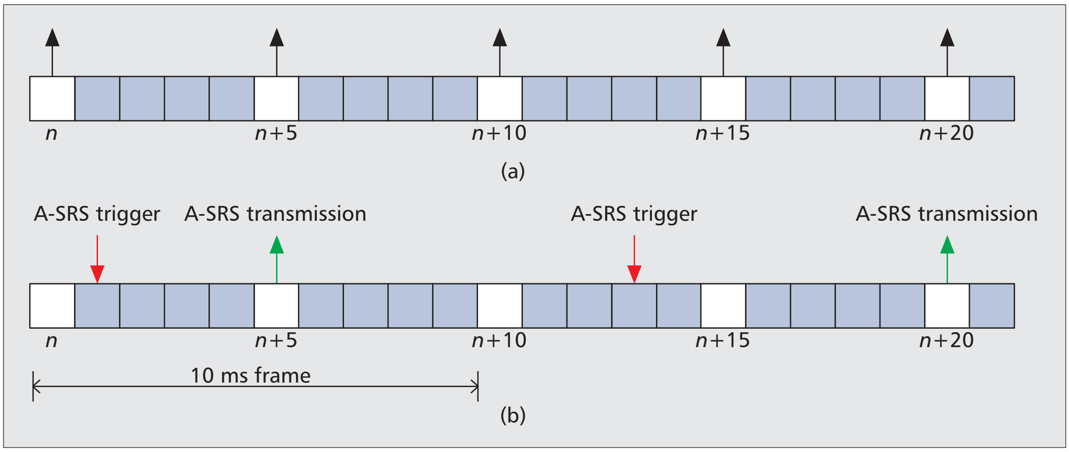


Figure 4. *Comparison of P-SRS and A-SRS transmission.*

A-SRS control signaling bits are piggybacked either in a downlink assignment scheduling downlink data transmission or in an uplink grant scheduling uplink data transmission in order to minimize signaling overhead.

off for non-identical-band MU-MIMO.

Different OCC for UE: For the sake of non-identical-band MU-MIMO, different OCC values of [+1 +1] or [+1 -1] are defined for different UE.

SGH Disabling — Assuming the use of non-identical-band MU-MIMO, OCCs can orthogonalize DMRS only when SGH is disabled, that is, the root ZC sequence is the same between the first and second slots. Therefore, LTE-Advanced allows disabling SGH in UE-specific manners, in which case the same root ZC sequence is used among slots/subframes.

EVOLUTION OF SOUNDING REFERENCE SIGNALS

Background — LTE Release 8 SRS is based on the extended ZC sequence [4], which is periodically transmitted in the last SC-FDMA symbol of a subframe. UE units are multiplexed in the time and frequency domains, for which sounding subframes of periodicity T_{SRS}, frequency comb, and bandwidth are UE-specifically configured. Similar to DMRS, up to eight orthogonal SRS transmissions can be CDM'ed in the same bandwidth using different CS of the root ZC sequence.

Achieving the spectral efficiency gains promised by four-layer uplink spatial multiplexing is dependent on accurate CSI estimation, which, in turn, dictates up to a fourfold increase in sounding resources. Furthermore, the LTE-Advanced requirements [1] specified the support of at least 300 active users, without discontinuous reception, in a 5 MHz bandwidth, which is a 50 percent increase over the Release 8 requirements. Hence, it has been observed that the periodic nature of Release 8 SRS transmission is not flexible enough to support sounding from an increased number of antennas and/or UE units; nor is it nimble in sounding the channel in response to dynamic fluctuations in traffic and channel conditions. This is partly because Release 8 UE is configured for sounding by semi-static RRC signaling, which incurs a larger signaling latency compared to physical layer dynamic signaling.

As a result of these limitations in Release 8 sounding, aperiodic SRS (A-SRS) transmission is introduced to complement periodic SRS (P-SRS) transmission, wherein an eNodeB dynamically schedules UE for one-shot SRS transmission on demand. In this manner SRS resources are not tied to a single UE unit until RRC reconfiguration by the eNB. This mechanism allows for efficient management of a fixed set of time/frequency/code SRS resources by a larger pool of UE/APs.

SRS Structure — Periodic and aperiodic SRS transmissions share a common set of cell-specific SRS resources (a subframe configuration period and a subframe offset, and a maximum SRS bandwidth). Different sets of UE-specific sounding parameters are independently allocated for P-SRS and A-SRS transmission including SRS bandwidth, periodicity, a frequency comb, and a cyclic shift [6]. UE is configured with a fixed set of subframes — A-SRS opportunities — on which it may be scheduled for A-SRS transmission. This reduces the eNB scheduling complexity because in any subframe only a subset of UE can be triggered for A-SRS transmission. A comparison of the timing relationship between P-SRS and A-SRS is shown in Fig. 4 where P-SRS and A-SRS have the same subframe offset, P-SRS has a transmission periodicity T_{SRS} = 5 ms, and A-SRS transmission opportunities occur at a periodicity of $T_{SRS,1}$ = 5 ms. A-SRS transmission occurs in subframe $n + k$ if downlink control information (DCI) conveying a positive A-SRS trigger is detected in subframe n and $k \geq 4$. The constraint of 4 ms is to maintain the same minimum timing response to a downlink assignment or uplink grant contained in a detected DCI.

Signaling Design — The desire to minimize downlink signaling overhead guided the choice of maintaining a semi-static configuration of A-SRS parameters similar to P-SRS configuration. Furthermore, A-SRS control signaling bits are piggybacked in either a downlink assignment scheduling downlink data transmission or an uplink grant scheduling uplink data transmission in order to minimize signaling overhead. Since the primary goal of A-SRS is to support multi-antenna sounding, some configuration flexibility is achieved by configuring three independent sets of parameters (sets 1, 2 and 3). A 2-bit SRS field is added to an uplink grant scheduling uplink SU-MIMO data transmission, where the value 00 indicates a negative SRS trigger and the

For both P-SRS and A-SRS a combination of the frequency comb and CS can be used to multiplex four APs' SRS in large delay spread channels, while for low delay spread channels or for UEs equipped with two APs, only different CS values are used to multiplex the SRS.

values 01, 10, and 11 schedule an A-SRS transmission utilizing the parameters indicated in sets 1, 2, and 3, respectively. On the other hand, a 1-bit A-SRS field is added to an uplink grant scheduling uplink single-antenna data transmission, and a separate set of parameters is indicated when a positive trigger (value 1) is detected in the uplink grant.

It can be seen in Fig. 4 that to satisfy the A-SRS transmission timing for a specific A-SRS opportunity, there are a limited number of subframes in which the eNB can send a positive A-SRS trigger. This scheduling constraint is even more severe for some time-division duplex (TDD) system configurations where only a few uplink subframes occur in a radio frame. Hence, to increase the scheduling opportunities for A-SRS transmission, Release 10 specifies a 1-bit A-SRS control field in some downlink assignments scheduling downlink data transmission. Another advantage for TDD of triggering A-SRS in downlink assignments is that uplink sounding can be used to support downlink beamforming by exploiting channel reciprocity. As such, the need for aperiodic sounding is decoupled from the direction of data transmission (uplink or downlink).

SRS Multiplexing for SU-MIMO — To ensure that there is no timing mismatch between CSI estimates from multiple antennas, UE is configured to simultaneously transmit SRS from all configured APs. The orthogonality of the CS breaks down as the frequency selectivity of the channel increases, and this degradation is more pronounced as the number of APs increases. Therefore, for both P-SRS and A-SRS, a combination of the frequency comb and CS can be used to multiplex four APs' SRS in large delay spread channels, while for low delay spread channels or UE equipped with two APs, only different CS values are used to multiplex the SRS. The CS and comb values for all APs are implicitly derived from the values in each of the semi-statically configured parameter sets.

Conclusion

In this article, technology advancements of reference signals to efficiently support enhanced transmission schemes newly introduced in LTE-Advanced were overviewed. For the downlink, design principles for the newly introduced CSI-RS and additional sets of UE-RS were reviewed. In particular, CSI-RS patterns, impacts on the legacy UE, and data resource element muting were examined for the CSI-RS, and benefits of UE-RS, UE-RS patterns and spreading sequences, control signaling, traffic-to-pilot ratio, and physical resource block bundling were discussed for UE-RS. For the uplink, enhancements of uplink DMRS and SRS were described in detail. Specifically, benefits of introducing orthogonal cover codes for uplink DMRS and aperiodic SRS were presented.

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