INTRODUCTION

Long Term Evolution (LTE), a cellular wireless communication standard based on orthogonal frequency-division multiplexing (OFDM), is now under commercial deployment by many cellular operators. LTE technology provides many enhancements compared with its predecessors, including high peak data rate, low latency, and spectrum flexibility. The ongoing deployment of LTE is based on Third Generation Partnership Project (3GPP) Release 8. In addition to minor enhancements in LTE Release 9, such as enhanced dual layer transmission, 3GPP has continued its effort to improve LTE with additional features. Thanks to this 3GPP effort, LTE-Advanced Release 10 was recently finalized and frozen; that is, the base feature set for Release 10 has been agreed. The primary goal of Release 10 standardization is to meet the International Mobile Telecommunications (IMT)-Advanced requirements for the fourth generation (4G) standards as defined by the International Telecommunication Union (ITU) [1].

The evolution of LTE toward LTE-Advanced makes it possible to meet IMT-Advanced requirements by the introduction of new features such as carrier aggregation, enhanced intercell interference coordination (ICIC) for heterogeneous networks (HetNets), and enhanced multiple-antenna transmission supporting up to eight downlink layers [1]. These new features require significant improvement of the user equipment (UE, the LTE term for handsets or mobiles), and pose various design challenges. For example, the need for advanced UE receivers has been pointed out in [2] for UE to enjoy the full benefit of HetNet deployment.

In this article, we focus on how this recent advancement of 3GPP standardization can affect UE receiver operation (i.e., reliable reception of LTE-Advanced downlink transmission). More specifically, we discuss advanced UE receiver signal processing algorithms to address physical-layer challenges. While most new LTE-Advanced downlink features are discussed in the following sections, relaying and coordinated multipoint (CoMP) transmission are not covered. For relay, the UE does not need to be aware of relay operation since the relay is transparent to the UE [3]. Thus, UE can benefit from deployment of relays without identifying them, and relaying does not impose big challenges for Release 10 UE design. For CoMP, its full support has been delayed and is under active discussion for Release 11.

In this article, we provide a high-level overview of the modem design challenges in supporting the Release 10 features, and suggest possible solutions. The main body of this article covers five primary issues for LTE-Advanced modem design: carrier aggregation, enhanced ICIC for HetNet, detection of eight-layer transmission, reference signals for enhanced multi-antenna support, and hybrid automatic repeat...
request (HARQ) buffer management. Concluding remarks are given in the last section.

**Carrier Aggregation**

LTE-Advanced supports aggregation of multiple component carriers. This feature enables system deployments with large bandwidth to achieve very high data rates, allows operators to deliver a better user experience by aggregating scattered spectrum, and supports interference management in heterogeneous networks via cross-carrier scheduling. With carrier aggregation, LTE-Advanced supports system bandwidth up to 100 MHz, with the potential of achieving more than 1 Gb/s throughput for downlink and 500 Mb/s throughput for uplink.

The component carriers can be contiguous within the same band, as shown in Fig. 1a, non-contiguous in the same band, as shown in Fig. 1b, or in different bands as shown in Fig. 1c. Each of the aggregated component carriers can have a different bandwidth. The component carriers that a UE needs to support are determined through a UE-specific configuration process and a dynamic activation and deactivation process. Each UE is configured with a primary component carrier (also known as Primary Cell or PCell). All the other component carriers can be configured as secondary component carriers (also known as Secondary Cells or SCells). The configured SCells are subject to activation/deactivation through either the activation/deactivation medium access control or the SCell deactivation timer maintained by the UE. This concept is shown in Fig. 1d. An SCell can be deactivated, e.g., when there is not enough traffic for the SCell. This allows a UE terminal to turn off part of the transceiver chain (e.g., radio frequency [RF] front-end and fast Fourier transform [FFT]) to save power. Due to this activation/deactivation process, the state of SCells can be changed frequently. As a result, radio link monitoring is only supported in the PCell but not in SCells to avoid complex UE behavior and additional control signaling overhead. Despite this kind of effort, the increased complexity due to physical downlink control channel (PDCCH) decoding and timing tracking of multiple component carriers cannot be avoided. However, it does not create any complicated technical issue, but extra hardware including additional PDCCH decoding and timing tracking blocks for additional component carriers and memory buffer to cope with a relative propagation delay difference among component carriers at the UE side.

The receiver RF filter design depends on the type of carrier aggregation. For carrier aggregation with intraband contiguous component carriers, either a single RF filter or two separate RF filters can be used. To use a single FFT to cover the contiguous component carriers, the carriers should be separated by integer multiples of 300 kHz — the least common multiple of the LTE channel raster (100 kHz) and LTE subcarrier.
In SIC, ordering does matter, and the strongest interference can be cancelled first. If the interference is not strong enough to be decoded, it can be ignored.

spatial (15 kHz). In that case, the contiguous component carriers can be separated in the digital baseband. The advantage of using a single RF filter is low hardware complexity due to a single RF chain for carrier aggregation. However, it requires an analog-to-digital converter and RF filter with larger bandwidth. Moreover, due to activation and deactivation of component carriers, there is a retuning issue when a single RF is used for these component carriers. When the status of an SCell is changed from activated to deactivated, the UE can save power by retuning its RF from an aggregated bandwidth including the SCell to a smaller bandwidth excluding the SCell. However, during this retuning procedure, some packets may be dropped due to RF transition time for retuning. In LTE, the impact of RF retuning to PDCCH is exacerbated because the PDCCH leads to loss of the entire physical downlink shared channel (PDSCH) subframe in the absence of control information required for decoding, which causes increased packet errors. RF retuning is closely related to the measurement of the deactivated SCell since the UE needs to retune its RF when ever the deactivated SCell measurement is required. Thus, LTE-Advanced should balance the packet loss due to RF retuning and the measurement of deactivated SCells to achieve optimal network performance.

For carrier aggregation with non-contiguous component carriers (in either the same band or different bands), separate RF filters and FFTs are needed. Moreover, harmonics and intermodulation products from an uplink interband carrier aggregation transmitter can desensitize the receive band or have considerable impact on other radio technology in the handset. Thus, elements of the RF like the transmit/receive filter with proper attenuation should be carefully considered. Moreover, to support multiband carrier aggregation, new UE modems need to include additional components such as band switch, diplexer, and duplexer. The additional insertion loss due to these components needs to be handled properly by using a higher-gain power amplifier or a better duplexer, and relaxing the RF requirement or implementation margin.

**Enhanced ICIC for HetNet**

A HetNet consists of low-power picocells and femtocells in addition to high-power macrocells [2]. In contrast to a traditional homogeneous deployment of macrocells where the data rate of end users at the cell edge can suffer, the deployment of picocells and femtocells can improve end-user experience connected to these cells. However, this benefit comes at the cost of additional intercell interference between heterogeneous cells. While a HetNet can be deployed in LTE Release 8/9, this cross-tier interference is effectively handled by enhanced ICIC, a recently developed interference coordination feature in LTE-Advanced Release 10. Note that picocells are deployed by operators, while femtocells are mostly deployed by end users, possibly in an unplanned manner. Moreover, a femtocell can restrict public access if it has a closed subscriber group (CSG). Thus, it is more difficult to manage cross-tier interference between a macrocell and a femtocell than between a macrocell and a picocell.

The use of carrier aggregation is a possible solution to manage cross-tier interference. For example, control signaling of a macrocell is assigned at one carrier, while control signaling of a pico/femtocell is assigned at the other carrier. The partition of control channels eliminates the possibility of cross-tier interference. However, depending on the availability of spectrum for operators, carrier aggregation may not be employed.

In the cochannel deployment scenario without carrier aggregation, resources should be partitioned in a more sophisticated manner to manage cross-tier interference because two heterogeneous cells share the same bandwidth. To minimize this cross-tier interference, an almost blank subframe (ABS) is introduced for enhanced ICIC, where most subcarriers remain unused, and thus its interference to other cell is limited. Even in ABS, some reference signals, like the common reference signal (CRS), and some essential control signals, such as the physical broadcast channel (PBCH), need to be transmitted to support legacy UE of Release 8/9.

Now, the necessity for advanced UE receivers and their modem design challenge come into play. Since CRS, synchronization signals, and PBCH are transmitted in ABS, they inevitably collide with signals from other cells. Even with recent standardization effort, this type of collision is unavoidable. An advanced UE receiver with interference cancellation techniques will still benefit from HetNet cochannel deployments, while legacy UE of Release 8/9 can maintain its connection to the macrocell thanks to interference management through ABS. The rationale behind this interference cancellation technique is that if the interference is strong, it can be decoded and cancelled one by one from the strongest interference; this is known as successive interference cancellation (SIC). In SIC, ordering does matter, and the strongest interference can be cancelled first. If the interference is not strong enough to be decoded, it can be ignored. However, imperfect interference cancellation can degrade the quality of measurements used for radio link monitoring, radio resource management, and channel quality indicator (CQI) feedback.

To illustrate the effectiveness of interference cancellation, let us consider the cell search procedure under enhanced ICIC as an example. If overlapping or adjacent cells are frame synchronized, even with ABS, synchronization signals (i.e., PBCH and synchronization signals (SSS)) of these cells will collide. For a homogeneous deployment, this may not be a problem since the UE just needs to attach to the cell providing higher downlink power (i.e., the cell with higher correlation of synchronization signals). However, in a HetNet deployment, the UE may want to attach to the cell providing lower downlink power. This could happen if the access to the cell with higher power is restricted (e.g., a CSG femtocell).
Figure 2a illustrates the cell search procedure with SIC. In this procedure, the UE identifies cells one by one starting from the cell with the highest power. However, PSS and SSS of the detected cell are cancelled before the next cell is detected. This SIC on synchronization signals can be applied until all cells are detected. In Fig. 2b, we consider a two-cell deployment scenario where the target cell power is $10$ dB less than the interfering cell power. It is clearly shown that the use of SIC is essential to reduce the detection error in the HetNet cell search procedure with enhanced ICIC. In general, the advanced UE receiver needs the capability of interference mitigation to enjoy the full benefit of HetNet deployment with the enhanced ICIC feature of LTE-Advanced.

**Detection of Eight-Layer Transmission**

The LTE-Advanced system should fulfill the ITU requirements of the downlink peak spectral efficiency of $30$ b/s/Hz. The peak spectral efficiency is the highest achievable data rate per overall cell bandwidth assuming error-free conditions when all available radio resources for the corresponding link direction are assigned to a single UE unit. While two- or four-layer transmission would be more prevalent even for the LTE-Advanced system, the required downlink peak spectral efficiency can only be attained using high-order antenna configurations (i.e., $8 \times 8$). The main challenge of high-order multiple-input multiple-output (MIMO) is computational complexity. Maximum likelihood (ML) detection is optimal in the sense that it minimizes error probability when the distributions of all data are equally likely. However, due to its high complexity in $8 \times 8$ MIMO systems with high modulation order, a direct implementation of ML detection might not be a viable option for such MIMO systems. Instead of ML detection, linear MIMO detection algorithms having lower complexity than optimal ML detection, such as zero-forcing (ZF) or minimum mean square error (MMSE), can be applied with interference cancellation techniques. However, both still have greatly inferior performance to ML detection.

Thus, several near ML algorithms such as sphere decoding (SD) [4] and K-best [5] have been introduced. Those algorithms are unceasingly being improved to achieve performance close to ML with lower complexity. In particular, the classical K-best detector attempts to output a list of size K consisting of the most likely values of the transmitted symbols based on observations, and is used for hard detection of symbols [5]. As K increases, the computational complexity increases while the performance improves.

Figure 3 shows the block error rate (BLER) performance and computational complexity comparisons of K-best with different K values and MMSE detection algorithms for an $8 \times 8$ MIMO system. It can be seen that the performance improvement of K-best becomes marginal as the value of K exceeds 256 for 16-quadrature amplitude modulation (QAM), while the computational complexity of K-best grows linearly with K.

**Reference Signals for Enhanced Multi-Antenna Support**

In LTE/LTE-Advanced, the evolved NodeB (eNodeB, the LTE term for a base station) transmits certain predefined reference signal sequences along with the data. These are employed by the UE to estimate the downlink channel for the twin purposes of feeding back channel state information (CSI) to the eNodeB and equalization of the downlink channel in the process of data demodulation. In LTE/LTE-Advanced, there are four non-overlapping CRS patterns (corresponding to four transmit antenna
ports), as shown in Fig. 4. Since the CRS is used for data demodulation, the density of the reference signals is high.

One of the requirements for LTE-Advanced is that it should support up to eight-layer transmission, which implies that there need to be at least eight transmit antenna ports. Toward this, a key change in the reference signal design philosophy from LTE Release 8 is the separation of the demodulation reference signals (DM-RS) from the channel state information reference signals (CSI-RS) in Release 10. This potentially saves significant reference signal overhead, as it allows the densely populated DM-RS to be UE-specific. In a particular resource block (RB), the eNodeB needs to transmit DM-RS only for the layers that are being transmitted to the scheduled UE, irrespective of the number of transmit antenna ports. On the other hand, CSI-RS continues to be transmitted from each of the antenna ports at the eNodeB to enable full CSI feedback from the UE.

In light of the new reference signal designs for LTE-Advanced, significant new challenges emerge from a modem design perspective, as discussed next.

**CSI-RS**

In order to provide for eight CSI-RS patterns, the density of CSI-RS in LTE-Advanced is significantly less than that of CRS. Specifically, there is only one CSI-RS resource element (RE) per RB per antenna port (Fig. 4). Furthermore, unlike CRS, which is transmitted in every subframe (every 1 ms), CSI-RS is expected to be transmitted only once every five or ten subframes. The sparse nature of CSI-RS poses a major technical hurdle for UE modem development in LTE-Advanced. In particular, advanced algorithms are needed for CSI-RS-based channel estimation and computation of the CSI feedback parameters such as CQI (i.e., modulation and coding rate) because existing methods may incur throughput degradation and/or result in a failure to meet the target BLER requirements. Our results in Fig. 5, discussed next, provide a glimpse of some of these issues.

Typically, algorithm design for CSI feedback involves the computation of an effective signal-to-noise ratio (SNR) metric. The effective SNR is a physical layer abstraction meant to convert a set of different SNRs, experienced during coded transmission over a frequency selective fading channel, into an equivalent SNR that would result in a similar BLER when transmitting over the static additive white Gaussian noise (AWGN) channel [7]. Using the computed effective SNR, and precomputed reference BLER vs. SNR curves for the AWGN channel, the UE can feed back the largest CQI that meets the target BLER requirement. With ideal channel state information at the UE, the preceding abstraction is known to work well. However, using standard channel estimation at the CSI-RS RE locations, we observe that the effective SNR prediction can be significantly erroneous. In Fig. 5a, we consider 50 different channel realizations and plot the following three effective SNRs:

- Predicted effective SNR with ideal CSI
- Predicted effective SNR with CSI-RS-based channel estimation
- The actual effective SNR

We can observe that with ideal CSI, the prediction matches the actual effective SNR closely, while with estimated CSI, there can be significant errors. This can result in inaccurate CQI feedback, potentially causing the downlink BLER to overshoot the mandated target BLER.

Next, we consider the impact of CSI-RS channel estimation on throughput performance. This entails not only CQI feedback, but also, and perhaps more crucially from a throughput perspective, the spatial preprocessing (i.e., PMI/RI) feedback, because channel estimation errors can result in suboptimal PMI/RI feedback, leading to throughput degradation. For a 2 × 2 MIMO system, Fig. 5b depicts the throughput as a function of the SNR. We observe that channel estimation errors result in about 2 dB performance loss in the low SNR regime.

Our results demonstrate the need to investigate advanced algorithms for CSI-RS channel estimation and CSI feedback. Possible strategies...
to improve the CSI-RS channel estimation performance could include exploitation of the time-frequency correlations (across different RBs and/or different subframes), for example, using a 2-D MMSE filter. This is accompanied by a caveat that such approaches hinge critically on the estimation of the channel’s power delay profile (PDP) and the Doppler shift, which pose significant technical challenges of their own. Potential benefits of exploiting these correlations are indicated by the results in Fig. 5b, wherein we have depicted the throughput gains obtained using a 2-D MMSE interpolator, with known PDP and Doppler shift.

**Figure 4.** Reference signals: locations and density of CRS, CSI-RS, and DM-RS.

DM-RS

LTE-Advanced DM-RS is expected to be used mainly for multilayer transmission supporting up to eight DM-RS antenna ports. DM-RS mapping to REs is illustrated in Fig. 4. DM-RS is multiplexed by a hybrid scheme of code-division and frequency-division multiplexing. For code-division multiplexing, the time-domain orthogonal cover code (OCC) or Walsh sequence is used [8]. At each UE receiver antenna, channel estimates associated with each transmission layer (or antenna port) are obtained by despreading the received reference signals with the known reference signal sequence and OCC. This orthogonal despreading with the scrambled OCC is valid when the channel is constant over reference signals (i.e., under static or slowly time-varying channels). Regarding precoding, UE can demodulate data in the PDSCH without precoding information because both data and DM-RS use the same precoder or beamforming matrix within the same RBs. The precoder itself is not specified in the specification, and its usage depends on eNodeB vendors.

In general, DM-RS channel estimation involves an interpolation using the reference signals. It is well known that a 2-D MMSE filter is an optimal linear filter minimizing the mean squared error of channel estimation [9]. The 2-D MMSE filter uses correlation information both in the frequency and time domains. Since the 2-D filter is computationally more complex than two similar 1-D filters, 1-D filters are frequently adopted and applied separately in the time and frequency domains. However, the lower complexity of 1-D filters comes at the cost of a higher error floor, as shown in Fig. 5c. Lower complexity methods of 2-D MMSE filters need to be identified to make them viable for implementation in UE modems. In addition, it is shown that the DM-RS channel estimation performance can be improved by considering the properties of time-varying channels.

With the advent of advanced LTE-Advanced transmission techniques, some aspects of DM-RS-based channel estimation merit investigation. First, the baseline of DM-RS channel estimation is performed per RB. This single RB-based channel estimation may restrict the availability and performance of channel estimation methods. For example, frequency domain correlation information required for MMSE-based interpolation cannot be directly obtained on a per-RB
basis, since the number of reference signals is very limited. Nevertheless, UE may use the pre-coding granularity in multiple RBs, and improve the channel estimation performance through RB bundling [8]. Second, multi-user interference besides intercell interference also needs to be considered when multi-user MIMO (MU-MIMO) schemes are used. When MU-MIMO is configured, the eNodeB may try to select precoding matrices that minimize the multi-user interference among co-scheduled UE. In practice, however, the precoded DM-RS at co-scheduled UE may not be perfectly orthogonal to each other. Due to non-orthogonal precoding and reference signal sequences of MU-MIMO transmission, interference cancellation schemes are required to obtain reasonable channel estimation performance. In practice, SIC can be adopted for interference cancellation, where interference is eliminated by repeating estimation and subtraction schemes.

HARQ BUFFER MANAGEMENT

The data channel uses a turbo code for forward error correction (FEC) and employs a stop-and-go protocol, hybrid automatic repeat request (HARQ), where a codeword can be punctured and transmitted in multiple attempts. Which of the bits are punctured in a given attempt is indicated by the redundancy version index. For each HARQ attempt that fails decoding, the UE sends a negative acknowledgement and waits for the next retransmission attempt. HARQ brings many benefits, including throughput maximization, latency control with time-interlaced HARQ processes, and fine control of system resource usage. However, HARQ is effective only if the UE has the memory to store the soft bits (i.e., soft channel bits) after decoding fails. This is because the probability of successful decoding of a single HARQ transmission can be very low, especially when the base station overestimates the channel strength or performs aggressive puncturing, where soft combining of multiple HARQ attempts is needed to ensure successful decoding.

Storage requirement is perhaps the biggest disadvantage of HARQ. Compared to LTE Releases 8 and 9, LTE-Advanced requires larger HARQ storage due to the higher throughput. Thus, it becomes crucial to reduce the storage requirement by managing the HARQ buffer efficiently. Table 1 lists the required buffer sizes for different UE categories, of which the last three are new additions for LTE-Advanced. Note that the UE capability is classified into several categories in LTE-Advanced [10]. User equipment from category 5, 6, or 7 must be able to store about 3.7 million soft bits. For UE category 8, the number is increased tenfold. Such storage requirements pose a big challenge for handset modem designers. Suppose that it takes four logic gates to store one bit, and each soft bit is represented by an 8-bit integer. Then, UE category 5 would require a gate count of about 117 million just for the HARQ data buffering. Thus, without efficient techniques for HARQ buffer management, such storage requirements would mean a very large die size for on-chip memory.

Fortunately, it is not necessary to store the soft bits at the original resolution. A soft bit is typically in the form of log-likelihood ratio, which

Figure 5. CSI-RS and DM-RS channel estimation. Impact of CSI-RS channel estimation errors on the a) accuracy of effective SNR prediction b) achieved throughput. c) DM-RS channel estimation performance with MMSE and linear interpolation.
can be represented by 8 bits accurately. When decoding fails, the soft bits can be compressed to a significantly lower resolution before sending to stations. In some cases a 1-bit compressed resolution is able to maintain a throughput loss of less than 1 dB in SNR. However, in high-data-rate scenarios, such low resolution causes significant throughput losses, especially when the effective FEC code rate is too high for a given SNR.

To improve the throughput performance in challenging scenarios, the compressed resolution needs to be higher than 1 bit. In particular, fractional rates can be achieved using vector quantization techniques [11]. Because soft bits belonging to the same modulation symbol are more strongly correlated than bits that do not, it is beneficial to group together soft bits that come from the same modulation symbol when vectorizing the log-likelihood ratio sequence to be compressed.

In addition to compression, HARQ buffer memory needs to be further managed via non-compressive techniques in case of carrier aggregation. For example, the required buffer size for UE category 5 is 3,667,200 soft bits divided equally among all configured downlink component carriers. The eNodeB, however, assumes a soft buffer size of 3,667,200 for rate matching per component carrier, regardless of the number of component carriers. While the number of soft bits received can exceed the required storage space, the UE can choose to store more soft bits than the specification requires. Because not all configured component carriers are fully utilized at all times, the UE can dynamically divide HARQ storage space among component carriers by assigning less/no storage to underutilized/idle component carriers and more to loaded component carriers. However, a mechanism should be in place to rebalance the memory usage when an underutilized/idle component carrier becomes busy.

**CONCLUSION**

LTE Advanced is a flexible wireless broadband technology that promises significant enhancements in the end-user experience. This article provides a high-level overview of UE modem design challenges in supporting LTE-Advanced Release 10 features and suggests possible solutions. Various challenges in the following areas are identified, and their implications and solutions to LTE-Advanced modem design covered: carrier aggregation, enhanced ICIC for HetNets, detection of eight-layer transmission, reference signals for enhanced multi-antenna support, and HARQ buffer management. By overcoming the challenges in UE modem design, LTE-Advanced will deliver on its promise of significant enhancements in the end-user experience.

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