LTE-Advanced: An Operator Perspective

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ABSTRACT

LTE-Advanced extends the capabilities originally developed in LTE within the 3GPP. Carrier aggregation is the most significant, albeit complex, improvement provided by LTE-Advanced. Bandwidths from various portions of the spectrum are logically concatenated resulting in a virtual block of a much larger band, enabling increased data throughput. Additionally, enhancements to MIMO antenna techniques in the uplink and downlink further increase the data throughput. Cell coverage is improved by means of relay nodes, which connect to donor eNode-Bs. To cope with the many varieties of cell types and sizes (macro, pico, femto), intercell interference control is enhanced to handle these heterogeneous networks. Operators hope to leverage LTE-Advanced to offer their mobile wireless customers a vastly superior user experience.

INTRODUCTION

The thirst for greater data rates exhibited by users of mobile wireless services has been on an exponential trajectory. Long Term Evolution (LTE)-Advanced seeks to improve voice quality and expand broadband data services, to deliver high-definition video and audio and other on-demand and real-time content in an "anything-anywhere-anytime" manner.

In addition, LTE-Advanced continues to advance means to lower latency and round-trip delays, reduce intercell interference, and support coexistence between the various flavors of cells — macrocells, micocells, femtocells, and so on. Relays are being designed to provide greater coverage, while using in-band backhaul via the existing radio interface.

In this article, operators representing a cross-section of the globe have come together to provide a perspective on expectations for LTE-Advanced from the operator point of view. Obviously, LTE-Advanced, as with all leading edge topics, has a multitude of aspects we would like to have covered; however, the following key topics are dealt with herein:

• Carrier aggregation — Pingping Zong and Jin Yang, Verizon (United States)
• Advanced DL MIMO techniques — Satoshi Nagata, NTT DOCOMO (Japan)
• Advanced UL MIMO techniques — Thomas Derham, Orange (France)
• Relaying — Prakash Bhat, Vodafone (United Kingdom)
• Coordinated multipoint TX and RX — Luis Campoy and Ignacio Berberana, Telefonica (Spain)
• Enhanced ICIC/HetNets — Xiaodong Shen and Guangyi Liu, China Mobile (China)

Aspects touched on but not limited to include: motivations for LTE-Advanced, primary use cases, scenarios, expectations, competitive pressures, device and infra-structure challenges, and deployment and operational costs.

CARRIER AGGREGATION

MOTIVATION

Wireless customers are increasingly using mobile devices as their main tool to surf the Internet, play games, stay connected with friends and family, and watch real-time news, favorite TV programs, or the latest blockbuster movie. Offering high-speed data over wireless networks to meet and encourage such ever-increasing service demands is of significant interest to the wireless operators around the world. The wireless industry has evolved from using second-generation (2G) technologies to today’s Third Generation Partnership Project (3GPP) LTE Release 8, with increasing spectrum efficiency more than 100 times. With the limitation of available contiguous spectrum being allocated and licensed to the wireless operators, carrier aggregation is needed to meet the International Telecommunication Union — Radiocommunication Sector’s (ITU-R’s) 1 Gb/s peak rate requirement for IMT-
Advanced. Carrier aggregation has been introduced to 3GPP LTE-Advanced work since 2009 as one of the key components for 3GPP LTE Release 10.

**AN OVERVIEW OF RELEASE 10 CARRIER AGGREGATION**

The 3GPP LTE Release 10 signaling specification, which was completed in June 2011, supports carrier aggregation of up to five component carriers (i.e., 100 MHz bandwidth) to achieve 1 Gb/s downlink peak rate and 500 Mb/s uplink peak rate. It supports two types of aggregation: intra-band contiguous spectrum aggregation and inter-band spectrum aggregation. The support of intra-band non-contiguous spectrum aggregation has been deferred to Release 11, which is to be completed by December 2012. Furthermore, the Release 10 carrier aggregation signaling specification supports the following downlink and uplink symmetry configurations: symmetric (i.e., same number of downlink and uplink component carriers) and asymmetric (i.e., more downlink component carriers than uplink component carriers). The downlink and uplink component carrier linkage is configurable via radio resource control (RRC) signaling. It is also worth noting that Release 10 carrier aggregation only supports backward-compatible component carriers. This ensures that non-carrier-aggregation-capable user equipment (UE, e.g., Release 8/9 UE) can transmit and receive on one of the carriers in a network supporting carrier aggregation.

For a UE in RRC_CONNECTED state, the UE is more flexible in simultaneous data delivery over multiple carriers. For example, during a large convention or sports event, LTE users could be interested in accessing a high data rate broadcast program (e.g., at 10 Mb/s), while still expecting the usual experience for unicast data services, such as voice over IP (VoIP), email, and web browsing. With Release 10 carrier aggregation, the throttling of any of the abovementioned services for that user can be avoided. Hence, when operators are challenged to provide a better user experience while facing a lack of wider contiguous spectrum, the flexibility in simultaneous data delivery over multiple carriers becomes increasingly important.

**POTENTIAL USE CASES OF RELEASE 10 CARRIER AGGREGATION**

Carrier aggregation supports a higher peak rate of up to 1 Gb/s with up to 100 MHz bandwidth. In the higher frequency bands, such as 3.5 GHz, an operator may be allocated and licensed more than 20 MHz of contiguous spectrum. Release 10 carrier aggregation enables such operators to provide higher peak rate and capacity without being restricted by the 20 MHz bandwidth upper limit set in LTE Release 8/9. In the lower frequency bands, such as 700 MHz, spectrum allocation and licensing is normally done in much narrower blocks (e.g., 6 MHz/block in the 700 MHz bands in the United States). For those bands, Release 10 carrier aggregation enables an operator to pool its spectrum resources together within the same band or across different bands to achieve higher peak rate and capacity.

Carrier aggregation also allows operators to provide multiple services simultaneously over multiple carriers. For example, during a large convention or sports event, LTE users could be interested in accessing a high data rate broadcast program (e.g., at 10 Mb/s), while still expecting the usual experience for unicast data services, such as voice over IP (VoIP), email, and web browsing. With Release 10 carrier aggregation, the throttling of any of the abovementioned services for that user can be avoided. Hence, when operators are challenged to provide a better user experience while facing a lack of wider contiguous spectrum, the flexibility in simultaneous data delivery over multiple carriers becomes increasingly important.

Furthermore, carrier aggregation can improve network efficiency and user performance by dynamically allocating traffic across the entire available spectrum. Carrier-aggregation-capable devices will report channel quality for carriers across a wide spectrum. This will improve resource allocation and handover in a heterogeneous network (HetNet), where both the number of carriers and the carrier transmit powers can vary significantly across the sites, with higher-power macrocells and lower-power pico- or femtocells. Both the macrocells and the pico/femto cells can transmit aggregated multi-
Further enhancement of DL MIMO technologies are required to improve user experience throughput and network capacity. Since the aims of introducing MIMO technologies are different according to the use case, various MIMO technology features need to be supported.

### SUMMARY

In this section, we provide an overview of the carrier aggregation feature supported in 3GPP LTE Release 10. With carrier aggregation, the bandwidth of the contiguous spectrum is less of a limiting factor in achieving a higher user peak data rate. With the ability of pooling multi-carrier spectrum resources together, carrier aggregation enables operators to utilize their spectrum holdings in a more flexible and efficient way.

### ADVANCED DL MIMO TECHNIQUES

#### MOTIVATION

To accommodate increasing traffic due to widely spreading smart phones, new mobile devices such as tablets, and various cellular applications, further enhancement of the LTE cellular networks is crucial for operators. Further enhancement of downlink (DL) MIMO technologies are required to improve user experience in terms of throughput and network capacity. Since the aims of introducing MIMO technologies are different according to the use case, various MIMO technology features need to be supported. For instance, user peak data rate enhancement might be important in indoor areas, and average user data rate (or capacity) enhancement might be more important in dense urban areas. Furthermore, it is important that these enhancements be supported in a backward-compatible manner for smooth migration from LTE to LTE-Advanced.

3GPP LTE Release 8 adopted MIMO technologies for DL transmission, supporting up to four spatial layers. Maximum two-layer DL MIMO transmission would be a standard configuration of the LTE deployment. For LTE-Advanced, further advancement of LTE has been envisioned in accordance with 3GPP operators’ requirements and the need to exceed the IMT-Advanced requirements provided by ITU-R [1]. Table 1 shows the downlink peak spectrum efficiency requirements and the capability of LTE and LTE-A systems. The ITU-R requirement can be satisfied by the LTE Release 8 capability supporting a maximum of four spatial layers. The LTE-Advanced requirements set by operators in 3GPP are more challenging and can be met by the enhanced MIMO capability supporting a maximum of eight spatial layers.

#### FEATURES OF LTE-A DL MIMO

LTE-Advanced adopted eight-Tx-antenna MIMO transmission with maximum spatial eight layers in DL to support high-end user terminals. Eight-Tx-antenna MIMO transmissions would be beneficial to boost peak data rates for isolated cell environments such as indoor deployments through spatial multiplexing gain, and enhance network coverage through beamforming or MIMO precoding gain. Combined with carrier aggregation with five component carriers, eight-layer DL MIMO achieves peak data rates of 3.0 Gb/s [2].

LTE-Advanced supports advanced multi-user (MU-) MIMO in the DL to improve the capacity of the network by spatially multiplexing multiple user terminals, where each user terminal would typically receive up to two spatial layers. The advanced MU-MIMO techniques would be beneficial for the capacity enhancement of highly populated urban areas. Advanced MU-MIMO is an essential feature to satisfy the ITU-R requirement of cell spectrum efficiency and cell edge spectrum efficiency for urban micro- and macro-cells [3].

For LTE-Advanced, transmission mode (TM) 9 has been newly specified to jointly support the maximum eight-layer single-user (SU-) MIMO and advanced MU-MIMO. TM9 is characterized by data demodulation based on demodulation reference signal (DM RS) and channel state information (CSI) measurement based on CSI RS. DM RS enables advanced beamforming and MIMO precoding to spatially multiplex multiple user terminals. For LTE-A, the DM RS structure has been extended to support maximum 8-layer data transmission. CSI RS enables efficient CSI — rank indicator (RI), precoding matrix indicator (PMI), and channel quality indicator (CQI) — measurement because CSI RS insertion density is sparse in time and frequency. In addition, a new codebook utilizing double codebook structure has been specified to support eight-Tx-antenna MIMO transmissions, where the new codebook particularly targets a closely spaced cross-polarized antenna arrangement that

<table>
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<th>Capability</th>
<th>LTE Release 8 capability</th>
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<th>IMT-Advanced (ITU-R) requirement</th>
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<td>Downlink</td>
<td>16.3 (4 layers)</td>
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Table 1. Peak spectrum efficiency requirements and capability of LTE-A DL (bits per second per Hertz).
phones, tablets, and notebooks) on which these media-oriented mobile devices (e.g., smart-phones, storage, etc) and user interface capabilities is spawning a new generation of mobile applications from which substantial volumes of multimedia content are generated by the user and uploaded to the network — examples include sharing of photos and videos on social networks, and continuous upload of sensor data for location-based and wellness services. Furthermore, the maturity of cloud-based mobile services is increasing whereby certain functions such as storage, data processing, or even complete applications may be hosted on the network side. At the same time, enterprise users increasingly expect to be able to use cellular networks to continue use of their full range of enterprise applications (e.g., office, email, intranet, and database services) when they are on the road. All of these trends are placing increased demand on the cellular uplink, and it has become clear that further enhancement of the LTE uplink (UL) spectral efficiency using MIMO technology would be crucial for operators to meet demand for these services, while providing backward compatibility with existing LTE devices.

3GPP LTE Release 8 adopted a minimal MIMO implementation for UL transmission, supporting just a single spatial layer per UE, transmitted on a single antenna. If UE implements two transmit antennas, switched diversity may be employed whereby the active antenna is dynamically selected according to channel conditions. This approach avoids the need for additional RF transmit signal chains (PAs, filters, etc.) in cost-sensitive UE. In addition, it ensures that the low cubic metric (peak-to-average-power ratio, PAPR) properties of the discrete Fourier transform spread orthogonal frequency-division multiplexing (DFT-S-OFDM) UL signals are maintained, which is important for power-constrained transmissions from mobile devices. However, as shown in Table 2, LTE Release 8 UL spectral efficiency does not meet the requirements for IMT-Advanced, nor the much more ambitious target set by 3GPP taking into account the increased importance of the uplink as described above. Therefore, LTE-Advanced enhances the UL MIMO capability to support a maximum of four spatial layers. In addition to increased peak spectral efficiency, the enhanced MIMO capability is also designed to improve overall capacity, coverage, and user experience at the cell edge, which are key concerns for delivery of reliable and robust connectivity.

### FEATURES OF LTE-A UL MIMO

LTE-Advanced adopts four-transmit-antenna SU-MIMO transmission with a maximum of four spatial layers in the UL for high-end user termi-
LTE-A provides significant gains with two transmit antennas, so these smaller devices will still benefit. There are also challenges to deploy the corresponding four receive antennas in base stations, which are largely common to the implementation of enhanced DL MIMO.

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LTE-Advanced also supports MU-MIMO in the uplink, where two UE units may transmit up to two spatial layers each - this can be considered an extension of virtual MIMO (V-MIMO) supported in LTE Release 8. The key point of MU-MIMO is that even if the UE units have less than four transmit antennas (e.g., lower-end or smaller devices), they may be paired in order to obtain, on aggregate, the same peak spectral efficiency as for SU-MIMO.

Furthermore, LTE-Advanced introduces transmit diversity for the uplink control channel (PUCCH) whereby the multiple antennas are used to enhance robustness at the cell edge, and/or to reduce inter-cell interference by allowing reduction of control channel transmit power, which fundamentally improves network coverage and reliability.

A new UL transmission mode, TM2, has been specified that allows the eNodeB to instruct the UE to dynamically switch between multiple-antenna (including spatial multiplexing) and single-antenna modes (e.g., according to channel quality). TM1 specifies single-antenna mode only, corresponding to the LTE Rel-8 uplink scheme. Data demodulation is based on an evolution of the uplink demodulation reference signals (DM RS) defined in LTE Rel-8 to support multiple spatial layers. Sounding reference signals (SRS) are transmitted from each antenna separately, under control of the eNodeB to manage overhead, and enable the eNodeB to efficiently determine CSI and hence control the UE transmissions through rank indicator (RI), precoding matrix indicator (PMI) and channel quality indicator (CQI) feedback. The PMI codebook is specially designed so the cubic metric of transmitted signals from each antenna is not degraded even for multiple spatial layers, and also emulates Rel-8 antenna switching, which may allow one PA to be switched off to reduce power consumption if not needed.

**LTE-A UL NETWORK DEPLOYMENT**

The key challenge to implement UL MIMO enhancements will be how to integrate multiple transmit antennas and RF signal chains within the UE device packaging, while achieving the low mutual correlation required for maximum gains from spatial multiplexing and minimizing power consumption (especially in battery powered devices). UE units comprising four transmit antennas are more likely to be physically large devices (e.g., tablets,notebook PCs), where fortunately the throughput requirements are typically also the highest. For devices such as smartphones and dongles, overcoming the constraints of reduced antenna efficiency and increased mutual coupling within the small form factor is challenging, although various R&D activities on highly compact wideband antenna arrays are continuing. In any case, LTE-A also provides significant gains with two transmit antennas, so these smaller devices will still benefit. There are also challenges to deploy the corresponding four receive antennas in base stations, which are largely common to the implementation of enhanced downlink MIMO.

**RELAYING**

**MOTIVATION**

Operators have seen continued growth in data usage with increased numbers of smart devices (smart phones, USB devices, laptops/tablets, etc.). Furthermore, operators will be required to support diverse sets of application data rate requirements from low-data-rate machine-to-machine applications to high-data-rate applications such as IPTV. This requires operators to continually improve system capacity and coverage while meeting the challenges presented by the cost saving requirement. Fiber coverage as a backhaul solution will improve but will not reach everywhere. The operator is then presented with a challenge of improving capacity/coverage using either additional sites, more spectrum, or investing in a more spectrum-efficient technology. Not all the options are economical or feasible due to constraints such as cost and deployment (site acquisition, regulatory constraints, etc.).

Whilst many solutions are envisaged to meet the challenges posed, small cell deployments look promising as a way to improve coverage and capacity demand. From an operator perspective, macro cells could be designed and deployed from the outset to support clustering of low-powered cells. LTE will be extensively deployed on high carrier frequencies (i.e., 2.6 GHz). Furthermore, the majority of mobile traffic is generated indoors. Coverage improvements would then be key to meeting customer expectations. Heterogeneous networks with many different types of small cell solutions will increasingly be deployed to address the need for capacity improvements. From a user’s perspective, being closer to the cell should result in larger battery savings (due to reduced transmit power) and improved throughput.

There are several solutions for coverage improvements. These include solutions such as low-powered eNodeBs with traditional backhaul (e.g., microwave), repeaters with improved antenna gains and echo cancellation techniques, and open femtocells. For many deployments, the backhaul could present a considerable challenge. Microwave backhaul, although successfully used in macro deployments, needs to address many issues before it can be widely applied to small cell deployment. The availability of smart products in license exempt bands makes WiFi a strong candidate; however, propagation characteristics of 5.8 GHz for specific deployments need further consideration. The digital subscriber line access multiplexer (DSLAM) for backhaul is a cheaper option; however, availability and limited UL data rate represent significant issues. Fiber is an attractive solution, although very expensive and requiring a longer time to deploy. These challenges with backhaul can be addressed by self-backhauling relay nodes.

Relaying for small cells is an area where ven-
Relaying provides better fairness to users with homogeneous user experience; this comes at the cost of additional donor eNodeB access link resource utilized for the relay backhaul and also the associated latency. While inband relaying improves coverage, outband relaying will also improve capacity. Outband relay, however, would require economical sub-4-GHz spectrum dedicated for backhaul. Relays increasingly appear to be a possibility for rural broadband coverage improvement where fiber is not available. While no additional spectrum is required for backhauling for inband relays, relay deployments have their own challenges. High backhaul link quality is essential for the deployment of relays. Lower penetration of wired backhaul to customer premises in emerging markets makes relays the most attractive solution for indoor coverage in comparison to home eNBs (femtocells). However, no-touch (plug-and-play) deployment is essential if relays are to be considered for indoor deployment. One of the key metrics for deployment from an operator’s perspective is the cost per bit. For widespread deployment of relays for outdoor coverage improvements, key would be to justify the relative cost of relay deployment in comparison to small cell deployment with traditional wireless backhaul solutions such as microwave.

Relays can provide throughput enhancement and coverage extension. Support for LTE relays was standardized in 3GPP Release 10. With no impact on UE implementation, it is expected all LTE UE should be able to benefit from relay node deployment. Relay nodes (RNs) connect wirelessly to the donor cell served by donor eNodeB and can be classified as transparent or non-transparent. Non-transparent relay controls cells of its own (similar to eNodeB), and has a unique physical-layer cell identity; the same radio resource management (RRM) mechanisms as normal eNodeB are used and shall appear as a Release 8 eNB to Release 8 UE. Non-transparent relays can be further classified as type 1, type 1a, and type 1b relays. A transparent RN is part of the donor cell, does not have a separate physical cell identity, and is a type 2 relay.

Type 1 relays are half duplex relays by definition and are unable to transmit to the UE and receive from the donor eNB simultaneously, and require resource partitioning between the wireless backhaul link and the eNB, and the access link and the UE.

Full duplex relays, on the other hand, can operate as either outbound relays (Type 1a) or inband relays (Type 1b) with enough spatial separation, filtering, or enhanced interference cancellation, thus requiring no specific resource partitioning.

Type 1 half duplex inband relay does not transmit any signal to UE when it is supposed to receive data from the donor eNB (Fig. 1). The relay then configures these subframes as multicast/broadcast single-frequency network (MBSFN) subframes (fake MBSFN) when UE units (including Release 8 UE) are not supposed to expect any DL transmission, avoiding any legacy UE measurement issues. The relay should still transmit the control region (including the reference signals).

Further enhancements to relay backhaul, such as advanced quality of service (QoS) management, carrier aggregation for backhaul, advanced MIMO schemes with support of 8 Tx antennas and up to 4 layers, improvements to relay control channel, header compression, and enhancements to support mobile relays such as increased handover robustness for group mobility and enhancements to combat Doppler for the high-speed scenario, are being considered for future releases (Release 11 and later) of 3GPP. While use of mobile relays is envisaged primarily for mass transit scenarios such as in buses and trains, the self-backhauling nature could be useful to provide emergency communication during disasters when infrastructure may have been impacted. Multihop relays is one other area that will require further study.

Relay nodes, due to the nature of their deployment (indoors, rooftops, lampposts, etc.) may be particularly vulnerable to vandalism and other malicious activities when security of the entire mobile network may be compromised. This requires additional security measures (physical as well as over the communication links). While ensuring security is an important aspect of any small cell deployment, relays with wireless backhaul require additional considerations for backhaul security to prevent any eavesdropping over the backhaul.

3GPP has specified security procedures for RN deployments (Fig. 2). Mutual authentication between RN and network is performed using Authentication and Key Agreement Protocol (AKA) during the RN attach procedure with credentials stored on a universal integrated circuit card (UICC; Fig. 2). Binding of RN and USIM is based on either symmetric preshared keys or certificates. In either case, operators will need to provision special RN-aware UICCs for RNs. Control plane traffic, and optionally user plane traffic, is integrity protected.

In summary, from an operator perspective, relays could be a viable coverage (indoor and outdoor) and capacity improvement tool. Relays could be an important enabler for dense small cell deployment. Future evolution of relays such as mobile relays and multihop relays could further improve the user experience. Small low-power relays could encourage and provide opportunities for further innovation and vendor differentiation from cost and performance perspectives. Specific consideration of robustness of the backhaul link is required as several site con-
straints for deployment of relays may result in less than desirable performance for backhaul.

**COORDINATED MULTIPOINT TX AND RX**

**MOTIVATION**

Coordinated multipoint (CoMP) TX/RX aims to increase the throughput available to UE at the cell edge, enhancing network throughput by means of combining a cluster of base stations (BSs) to simultaneously serve selected UE.

Convergence trends for fixed and mobile solutions have been widely advertised for more than a decade, and are now a reality. Users are largely technology agnostic, and increasingly expect seamless experience with a range of devices, applications, and services being offered. Therefore, the challenge is to offer users the same quality of experience (QoE) perceived from their fixed broadband service but ubiquitously.

Therefore, the challenge is to offer users the same quality of experience (QoE) perceived from their fixed broadband service but ubiquitously. However, the value of SINR, which limits available BS-UE throughput, degrades from the UE near the base station to the UE approaching the cell edge due to the attenuation of the received signal strength and the increase of interference from other BSs or UE. As a consequence, the QoS experienced by users at the cell edge could be severely degraded if no coordination is present among different BSs.

3GPP has developed different procedures to overcome this degradation: fractional frequency reuse (FFR) in 2G systems, code division in 3G systems, and enhanced intercell interference coordination (eICIC) in 4G systems. However, all of them are based on arrangements (in a more or less dynamic manner) for sharing the radio resources (RRs) among neighboring BSs in order to serve users at the cell edge.

A new approach, currently discussed for 3GPP Release 11, is CoMP, which provides a further step in the coordination of RRs among BSs. CoMP is not only based on RR sharing, but also takes advantage of the transmission and reception capabilities of neighboring BSs to increase SINR in both the UL and DL.

**COMP OVERVIEW**

CoMP is one of the important features of 3GPP LTE-A Release 11, with several techniques competing to prove enhanced performance for a set of scenarios agreed on by a large number of the operators participating in the 3GPP.

CoMP technologies could be classified as: 

- **DL CoMP:** In this type, more than one BS transmits signals in a coordinated manner to UE as if it was a single transmitter with multiple antennas geographically distributed. BSs are clustered (either flexible or, more easily, fixed clusters) coordinating DL transmission among all of them.

The main DL CoMP technologies are:

- **Coordinated scheduling,** in which one entity (usually one of the BSs in the cluster) assumes the scheduling functionalities of all the BSs in the cluster. For this technology to work, all DL channel state information (CSI) from all BSs to the targeted UE are needed. Therefore, mechanisms should be implemented for the UE measured CSI to be sent to master BS. Any UE is served only by one BS, and therefore user data only needs to be present at its serving BS.

- **Coordinated beamforming,** which uses CSI to precode transmitted signals in order to avoid interference from different cells in a UE DL channel. Beamforming precoding can be done...
CoMP deployment considerations

One major drawback of CoMP is the impact this feature has on the backhaul.

Depending on the selected technique, if every cell is not at the same site (intracell deployment), CoMP technology will demand new requirements on backhaul links:

- High data rate between the master BS and other BSs (or radiating points) in the cluster. In the more demanding scenario, the MAC packet data unit (PDU) will be generated at the master BS along with the decision on PRB allocation, and modulation and coding schemes (MCS). In this scenario the master BS is in charge of the HARQ management of all BSs.
- Specific control and signaling among the master BS and the rest of the cluster BSs will be required, to exchange CSI information and commands with very low latency, since CSI may be referred to radio channels with coherence time below 1 ms.
- Time synchronization requirement, in order to align radio frames transmitted from different BSs to the UE.
- Phase synchronization, in case of coherent techniques previously discussed.

The technology that could provide the highest system gains is joint processing with coherent transmission, applied to cells geographically distributed at different sites, but this is also the technology that presents more demanding requirements from the backhaul. It should also be noted that hybrid technologies could be implemented, mixing the proposed technologies, each leading to a different set of requirements for the backhaul.

The real performance of some CoMP techniques depends on traffic load and SINR distributions that are not easy to predict/model. Even more, the high volume of CSI information over real X2 interfaces is subject to quantization error, delays, and increased acknowledgment (ACK)/negative ACK (NACK) round-trip time (RTT), which may have an impact on the technology's performance.

The time delay in information sharing leads to CSI mismatch with actual values. According to [4], in order to take advantage of joint non-coherent CoMP, X2 delay should be in a range of 1 ms or lower, meaning that care should be taken in designing the backhaul architecture. There is also a dependence on the gain obtained by CoMP technology and the traffic load in the cells involved; the gain reduces with increase in traffic load.

For practical deployment of some CoMP techniques changes will be needed not only in BS performance, but also in the UE’s, in order to measure and send the CSI CQI/PMI/RI values related with all the BSs involved in the cluster. Time-division duplex (TDD) may benefit from channel reciprocity.

Another factor to be taken into account, depending on the CoMP technique selected, is the possible degradation of the gains depending on the accuracy of time and phase synchronization.

It is not only the backhaul that will require some changes for the introduction of CoMP, but also over-the-air control channels. One of the more significant changes is the one related to the physical downlink control channel (PDCCH), for which an enhanced version, E-PDCCH, with an increase of the number assigned resources is currently being discussed for 3GPP Release 11, in order to be used for multiplexing control information of multiple UE units.
### Summary

An intense research effort on CoMP technologies is currently taking place, and a Work Item has been opened on the subject in 3GPP for Release 11. This Work Item is receiving a great amount of results from different vendors with different approaches, from the simplest coordinated scheduler and beamforming to the most sophisticated coherent joint transmission techniques.

Previous results on the selected scenarios tend to support that these technologies are not worthy to increase the spectral efficiency average over the full cell coverage. Results indicate gains of 2 to 3 percent, or even decreases of 2 percent, depending on the used technology.

These results point out that the real value of CoMP technology is the enhancement of cell edge UE performance. The gain in spectral efficiency on these cell edge UE units reported reach up to 80 percent with more sophisticated (and more backhaul demanding) mechanisms, but even simpler coordinated scheduler results show gains of 15 to 20 percent.

Therefore, CoMP technologies will represent in the future a way to guarantee the expected QoE of cellular users, avoiding the current bottleneck of coverage in cell edges. For these technologies to become really deployed, modifications and tight requirements may be needed on the backhaul interfaces. Even more, since its applications will be focused only on cell edge users, a dynamic UE selection mechanism of UE in which CoMP technologies are going to be applied should be developed.

### Enhanced ICIC/HetNets

#### Motivation

To provide flexible capacity expansion or offloading, it is important to ensure that LTE-Advanced provides efficient support for a mixture of macrocells and low-power eNBs. Macro eNBs with high transmit power and high antenna height are deployed to provide coverage, whereas some low-power nodes, such as microcells, picocells, HeNBs, and RNs, are deployed for coverage extension or offloading. In order to alleviate the complexity of network planning and optimization in hierarchical cellular deployment, the macro eNB and low-power nodes are allocated with different carrier frequencies, and thus the interference between macro and micro/pico can be ignored.

On the other hand, as the spectrum available for a cellular system is rare and expensive, it is preferred that the macro eNB and low-power nodes share the same carrier as cell splitting and thus higher network capacity are expected from the operator perspective. Such a deployment scenario is named heterogeneous network (HetNet), where severe interference between macro eNBs and low-power nodes may happen. Consequently, the enhancement of 3GPP Release 8/9 ICIC mechanisms is important to efficiently support HetNet deployment.

### What HetNet Can Offer

Heterogeneous deployments are deployments where low-power nodes are placed throughout a macrocell layout. A baseline deployment scenario for HetNet is described in Table 3.

### Characteristics of HetNet

Co-channel deployment is one efficient way to utilize spectrum resources as much as possible. For an LTE system, the interference characteristics in a HetNet deployment can be significantly different from a homogeneous deployment in co-channel deployment.

- **For a CSG cell, such as a macro and HeNB (CSG) co-channel deployment**, CSG cell transmission causes interference in macro UE. If the macro and HeNB are co-channel deployed, a macro user with no access to the CSG cell will be interfered with by the HeNB: the DL SINR of some macro UE near the HeNB is around -60 to -20 dB, which causes radio link failure (RLF) and deteriorates the UE experience.

- **For an OSG cell, such as a macro and pico/relay cell co-channel deployment**, path-loss-based cell association (e.g., by using biased RSRP reports) may improve the UL but at the cost of increasing the DL interference of non-macro users at the cell edge. For macro with pico cells within coverage, a biased RSRP scheme leads to heavy DL interference to pico-cell edge users. Figure 2 shows DL wideband geometry distribution with different values of bias. With 6 dB bias or larger, the outage of wrong or missed decode PDCCH joint with PCFICH is greater than 1 percent if required demodulation SINR of PDCCH is assumed to be ~5 dB. Then it is natural to introduce the eICIC solution to mitigate dominant interference.

### Features of eICIC Techniques

To deal with the severe interference between a macro eNB and a low-power node, carrier aggregation (CA)-based solutions are attractive for situations with large availability of spectrum and UE with CA capability. For non-CA (i.e., co-channel) scenarios, HetNets afford interference suppression, where a dominant interferer may prevent some UE from establishing/maintaining reliable communications with corresponding serving cells. Non-CA-based solutions are important to enable efficient HetNet deployments with small bandwidth availability and UE without CA capability.
The interference conditions are expected to change from location to location (due to the possibly lower level of network planning of these deployments) and from time to time (due to the variable traffic load at each node). Here, coordination of control and data channel interference is important to maintain the DL and UL cell coverage, and thus good data channel performance.

For a data channel in 3GPP, PDSCH resources can easily be coordinated in the frequency domain via a traditional 3GPP Release 8 ICIC mechanism (e.g., RNTP, HII, and OI). All of them exchange overload or interference indications between different eNBs over each band in the frequency domain. Thus, it requires backhaul support via either X2 or S1.

For the control channel, several techniques are discussed in LTE-Advanced standardization.

Time domain: Severe interference from an aggressor cell dominates the performance of a victim cell. Interference varies from one subframe to the next. Then one approach to restrict transmission in the time domain is naturally to consider as a valid tool to create an interference-free subframe among cells. The subframe to be allocated to enable interference-free transmission in the time domain is called the almost blank subframe pattern of a cell. Muting the whole subframe is sufficient enough to create interference-free resources. However, in order to keep backward compatibility to legacy UE for the purpose of broadcasting system information, maintaining UE measurements and UE synchronization, in most cases the following parts are still left from a backward compatibility perspective:

- Transmission of CRS in order not to impact legacy UE.
- SIB-1 contains information relevant when evaluating if UE is allowed to access a cell and defines the scheduling of other system information.
- PSS/SSS/PBCH carriers synchronization signals and system information transmitted on BCH.

In a time domain scheme, the resource for an almost blank subframe should be coordinated among neighboring cells in a semi-static way. Time synchronization between the cell layers is also required for this approach.

Time domain extension of Release 8/9 backhaul-based ICIC has some impact on the X2/S1 interface or operations, administration, and maintenance (OAM), RRC signaling, and RAN4 measurement. A bitmap pattern is used to indicate the almost blank subframe pattern of a macrocell to a low-power node. From the UE perspective, RRC signaling shall also be provided for resource-specific RLM/RRM/CSI measurements. From the RAN4 measurement perspective, UE shall be signaled which subframe the UE should use for measurement and CSI; note that this is not applicable for Release 8/9 UE.

eICIC, specified in 3GPP Release 10, defines UE performance requirements to enable significantly improved detection of control and data channels in the presence of dominant interferers for FDD and TDD systems.

Frequency domain: Traditional Release 8 control channels span a whole transmission band in the first 1–3 OFDM symbol(s) in a subframe. Thus, in a frequency domain scheme, traditional the Release 8 ICIC scheme is not applicable to control channel.

**Power setting:** For CSG interference on macro transmission or CSG transmission on the DL, coordination transmission power between aggressor and victim cells could alleviate interference. This DL power setting is applicable for CSG HeNB only. The power setting by different schemes show different gain in term of UE wideband SINR [5]. However, DL power setting for HeNB can improve the DL SINR, although it is not enough to satisfy the control channel demodulation requirements.

**Outlook on Future**

**3GPP Standardization of eICIC**

3GPP Release 10 kicked off an eICIC Work Item, “Enhanced ICIC for non-CA-based deployments of heterogeneous networks for LTE,” from RAN#47 in March 2010. The core part of the eICIC WI was finalized in RAN#52 in June 2011. Among a lot of techniques and solutions discussed, only the time domain solution for the time being will be included in Release 10 eICIC due to the tight schedule for that Release.

A further enhanced ICIC Work Item, “Further Enhanced TDM-based ICIC for LTE,” was begun at RAN#51 in March 2011 to solve a remaining issue not considered in Release 10. It could be studied over a very broad area to further enhance ICIC technique by considering:

- Data channel ICIC enhancements, such as FDM/TDM coordination and enhanced signaling for resource allocation
- Higher-layer enhancements, such as for idle mode operation and mobility enhancements
- Uplink enhancements such as UL interference mitigation for macro-pico and macro HeNB.
- Identifying interference scenarios stemming from different UL/DL configurations in TDD and corresponding CSI reporting requirements

With growing demand for data services, traditional deployment (as illustrated in the first item in Fig. 3) is becoming increasingly challenging to meet the required data capacity and cell edge spectrum efficiency through simple cell splitting. Cost-efficient deployment (in terms of both operating and capital expenditures), deployment speed, and simplification are important from operators’ perspective. Cell splitting is not always possible in an operator’s network deployment. Capacity expansion (e.g., multicarrier) is considered when the operator has sufficient spectrum resources (as illustrated in the second item of Fig. 3). With limited spectrum resources, Release 10 eICIC is important for efficient support of highly variable traffic loads as well as increasing complex network deployment scenarios with unbalanced transmit power nodes sharing the same frequency (the third item in Fig. 3). Release 10 eICIC brings a bright future for HetNet deployment with lower site acquisition cost and higher spectrum reuse utilization. This gives
the most deployment opportunities for Release 10 eICIC.

REFERENCES


BIOGRAPHIES

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