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# Radio Interface Technologies for Cooperative Transmission in 3GPP LTE-Advanced

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**SUMMARY** This paper presents an overview of radio interface technologies for cooperative transmission in 3GPP LTE-Advanced, i.e., coordinated multi-point (CoMP) transmission, enhanced inter-cell interference coordination (eICIC) for heterogeneous deployments, and relay transmission techniques. This paper covers not only the technical components in the 3GPP specifications that have already been released, but also those that were discussed in the Study Item phase of LTE-Advanced, and those that are currently being discussed in 3GPP for potential specification in future LTE releases.
***key words:*** *LTE-Advanced, CoMP, eICIC, relay*

## 1. Introduction

After enthusiastic efforts for standardization in the 3rd Generation Partnership Project (3GPP) and development, a commercial Long-Term Evolution (LTE) service was launched in Japan in December 2010. LTE provides full IP packet-based radio access with low latency and adopts intra-cell orthogonal multiple access schemes such as orthogonal frequency division multiple access (OFDMA) and single-carrier frequency division multiple access (SC-FDMA) in the downlink and uplink, respectively [1], [2]. Moreover, in the 3GPP, standardization efforts towards an enhanced LTE radio interface called LTE-Advanced (LTE Release 10 and beyond) are ongoing. In the beginning of 2011, specifications for LTE Release 10 were finalized to complete submission to the International Telecommunication Union Radiocommunication sector (ITU-R), and technical discussion regarding LTE Release 11 was initiated in the 3GPP.

In LTE initial release, i.e., LTE Release 8 specifications finalized in 2008, the radio interface was designed basically focusing on traditional cellular deployments associated with transmission between the base station, called an eNB (enhanced Node B), and user equipment (UE) as in 3G mobile communication systems. In LTE-Advanced, enhanced network deployments based on cooperative transmission techniques have been actively investigated to achieve higher system performance and more efficient/flexible network deployments. Figure 1 illustrates cooperative transmission techniques in LTE-Advanced, which are discussed in the paper. Coordinated multi-point (CoMP) transmission/reception is based on the transmission techniques using cooperation among multiple cells or geographically separated transmission points. The enhanced inter-cell interference coordination (eICIC) for heterogeneous deployments is a transmission technique that utilizes cooperation between cells or nodes with different transmission power levels. The relay transmission techniques utilize cooperation between eNB and relay nodes (RNs) or between a UE and RNs to extend the coverage or capacity. In the 3GPP, some radio interface technologies to support such cooperative transmission techniques have already been specified in LTE Release 10, and their further enhancements are being investigated for the specification of LTE Release 11 and beyond.

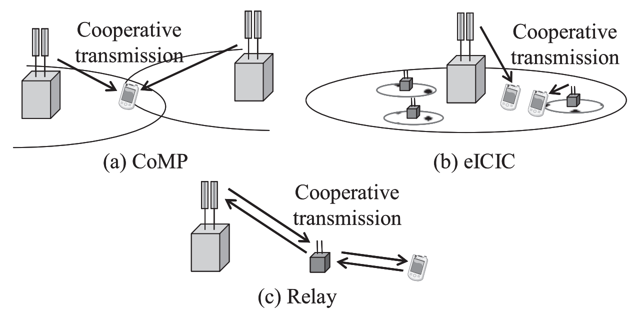


**Fig. 1** Cooperative transmission techniques in LTE-Advanced.

This paper presents an overview of the LTE-Advanced standardizations and a survey of the related research to explain the radio interface technologies for cooperative transmission such as CoMP, eICIC, and relay in LTE-Advanced. In the paper, CoMP, eICIC, and relay topics are explained in Sects. 2, 3, and 4, respectively. Note that the scope of the paper includes not only Release 10 specifications, but also technical discussions held during the Study Item (SI) phase for LTE-Advanced (LTE-Advanced SI) [3] and further advanced techniques that may be specified in future LTE releases.

## 2. Coordinated Multiple-Point Transmission and Reception

The evolution from W-CDMA to OFDMA/SC-FDMA in LTE has enabled orthogonal multiple access within a cell. On the other hand, inter-cell interference, due to static single frequency reuse, is still a bottleneck for further improving the spectrum efficiency. Thus, for LTE-Advanced, CoMP

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transmission and reception techniques have been studied to improve the spectrum efficiency based on the idea of extending static single frequency reuse to dynamic radio resource orthogonalization among cells [4]. In the 3GPP, the term "CoMP" was defined during the LTE-Advanced SI [3], where basic technologies and terminologies related to inter-cell cooperative processing or network multiple-input multiple-output (MIMO) technologies [5], [6] were investigated. In LTE Release 10, the specifications related to CoMP are limited to the downlink reference signal (RS) to support CoMP transmissions. However, for Release 11, further study is in progress under the new SI (CoMP SI) targeting further specification of CoMP related aspects. Note that downlink CoMP has been mainly discussed in the 3GPP since uplink CoMP could be implemented to a large extent without additional specifications for the physical layer. Thus, this paper focuses on the downlink aspects of CoMP technologies, which would match the scope of this journal.

### 2.1 Categorization of CoMP Transmission Schemes

In the LTE-Advanced SI, downlink CoMP transmission technologies are categorized into Coordinated Scheduling/Beamforming (CS/CB) and Joint Processing (JP), where JP is further categorized in to Joint Transmission (JT) and Dynamic Cell Selection (DCS). Each transmission technology may require different standardization effort, and which one should be supported is under investigation in 3GPP.

Figure 2(a) shows an example of CS/CB, where Physical Downlink Shared Channel (PDSCH) is transmitted only from the serving cell, whereas scheduling and beamforming are coordinated among cells. For example, as depicted in Fig. 2(a), each cell can calculate beamforming weights for its scheduled UEs such that interference to the scheduled UEs in neighboring cells is mitigated. Then, the signal-to-interference and noise power ratio (SINR) of cell-edge UEs is improved and so is the cell-edge user throughput.

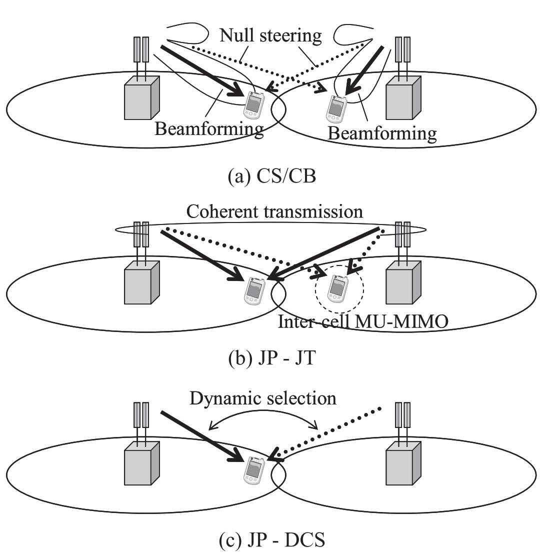



**Fig. 2** CoMP transmission schemes in LTE-Advanced downlink.

Figure 2(b) shows an example of JT of JP, where the PDSCH is transmitted simultaneously from the serving and non-serving cells. Precoding weights are calculated such that the signals transmitted from multiple cells are coherently combined at the UE. Then, the SINR of a cell-edge UE is improved and so is the cell-edge user throughput. Furthermore, multi-user (MU)-MIMO techniques can be applied to enable advanced MU-JT, where joint precoding is applied to the multiple antennas located on multiple cells to perform orthogonal precoding to the scheduled UEs on these cells. Theoretically, MU-JP could significantly improve not only the cell-edge user throughput but also the average cell throughput. However, MU-JT requires very accurate channel state information (CSI) that needs to be shared among cells to form orthogonal precoders [7], [8].

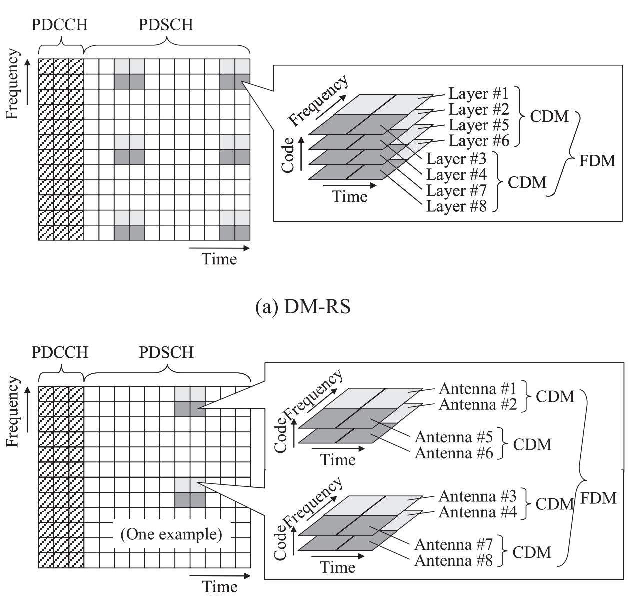
Figure 2(c) shows an example of DCS of JP, where the PDSCH is transmitted from a dynamically selected cell based on the instantaneous CSI at the eNB. Note that it is assumed in DCS that the serving cell from which the UE receives the Physical Downlink Control Channel (PDCCH), is not dynamically changed. Thus, DCS is categorized as JP since the PDSCH can be transmitted from non-serving cells. Furthermore, in DCS, if cells that are not selected for PDSCH transmission are kept muted instead of scheduling other UEs in the cell, the SINRs of cell-edge UEs are significantly improved, and the achievable cell-edge user throughput becomes closer to that of single-user (SU)-JT [4].

Finally, we would like to mention some CoMP related techniques that have not yet been fully discussed in the 3GPP. Coordinated power control among cells, referred to as a cell breathing technique [5], can be considered as an additional alternative to the 3GPP CS/CB scheme that performs coordinated scheduling and beamforming. In particular, in coordinated scheduling such as DCS, some cells are muted to mitigate inter-cell interference, which causes spectrum loss, whereas coordinated power control in cell breathing has an advantage in that it does not cause spectrum loss. Another cooperative transmission technique that is gaining attention recently is an interference alignment (IA) technique, where coordinated beamforming at the eNB and interference suppression at the UE receiver are combined [9]. Interference suppression receiver is also being studied in the 3GPP as an interference rejection combining (IRC) receiver [10]. A typical IRC receiver performs linear MMSE reception to suppress both intra- and inter-cell interference. Thus, when a UE has only two receiver antennas, it could suppress one dominant interfering signal due to the limited degrees of freedom. However, if IA is applied, multiple cells perform coordinated precoding to align interference to the neighboring cell UEs. Then, for example, a UE with 2 receiver antennas can suppress interference from two interfering cells.

### 2.2 Radio Interface for CoMP Transmission

In LTE Release 10, the downlink RS structure required for downlink CoMP transmission is specified, and thus CoMP transmission is possible in a UE transparent manner. Here, the UE transparent manner means that the UE can apply a unified demodulation scheme irrespective of whether or not CoMP transmission is applied at the eNB. Figure 3 shows the downlink RS structures specified for LTE Release 10. The downlink control signal transmitted on the PDCCH that spans up to the first 3 OFDM symbols are demodulated based on a cell-specific RS (CRS), and thus is transmitted only from the serving cells. On the other hand, the PDSCH is demodulated based on a UE-specific demodulation RS (DM-RS), the structure for which is shown in Fig. 3(a). Hybrid frequency division multiplexing (FDM) and code division multiplexing (CDM) structures are applied to support a maximum 8 layer MIMO transmission to achieve the peak spectrum efficiency of 30 bps/Hz. CDM is combined with FDM because CDM is beneficial in that it allows the same mapping pattern for the DM-RS irrespective of the number of the MIMO layers, and avoids transmit power boosting of the DM-RS compared to the PDSCH. What is noteworthy here is that the DM-RS is multiplexed only on physical resource blocks (PRBs) on which the PDSCH is scheduled, and the same transmission scheme, such as precoding, as the PDSCH is applied to the DM-RS. Thus, the UE does not need to be informed by the eNB what precoding weight is applied to the PDSCH, which enables various eNB implementations of the CoMP transmission strategy, such as null-steering for CS/CB and transmission from non-serving cells for JP in a UE transparent manner.

CSI is required at the eNB to support CoMP transmission. Particularly, CS/CB and MU-JT would require accurate CSI over multiple cells, and thus a trade-off between performance gain and the CSI feedback overhead should carefully be considered. Figure 3(b) shows the structure of the CSI-RS, which is used solely for CSI measurement. Unlike the DM-RS, which is precoded in the same manner as




(a) DM-RS

(b) CSI-RS

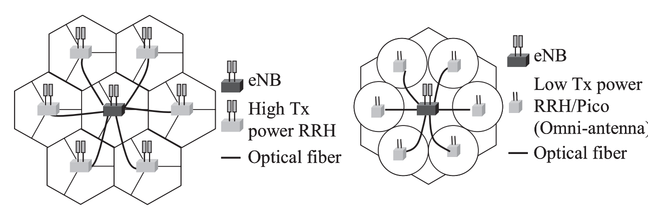
**Fig. 3** Downlink RS structure in LTE-Advanced.

the PDSCH, the CSI-RS is transmitted from each antenna port for a UE to measure the channel of each antenna port. A hybrid CDM and FDM structure is applied to multiplex multiple antenna ports. In addition, the density of the CSI-RS is 1 resource element (RE) per antenna port per PRB, and the CSI-RS is periodically transmitted, where the minimum duty cycle is 5 msec. Thus, overall the CSI-RS density is much sparser than that for the DM-RS. This is because the CSI-RS is used only for CSI measurement and thus requires lower density than the DM-RS, which is used for data demodulation. What is noteworthy here is that while LTE Release 10 does not support multi-cell CSI feedback, that is required to support cooperative processing for CoMP transmissions, i.e., scheduling and beamforming over multiple cell sites [7], [8], CSI-RS is designed to enable inter-cell CSI measurement for further CoMP feedback schemes. One such feature is PDSCH muting that achieves orthogonal CSI-RS transmission between cells, where each cell mutes the PDSCH REs corresponding to the CSI-RS REs of the neighbor cells. To achieve a high multiplexing capability of CSI-RS among cells, multiple CSI-RS patterns are specified per PRB, where Fig. 3(b) illustrates one example of such patterns.

### 2.3 Network Deployment for CoMP Transmission

Coordinated network architecture for CoMP could be based on inter-eNB distributed coordination or intra-eNB centralized coordination using remote radio heads (RRHs) [4]. In recent years, heterogeneous deployments, where low power nodes to deploy pico and femto cells are overlaid on macro cells, are gaining attention as a solution to offload increasing amounts of traffic with limited cost. Thus, the current CoMP SI in Release 11 studies CoMP transmission for the heterogeneous deployments as shown in Fig. 4(b) as well as the homogeneous deployments as shown in Fig. 4(a) considering both distributed and centralized coordination. Especially, Fig. 4(b) illustrates a promising network architecture for heterogeneous deployments, where pico cells with a small cell radius are overlaid on the macro cell with a large cell radius, and pico cells are deployed using RRHs that are connected to the macro eNB so that the central coordination is applied without latency issues for the coordination among cells. Furthermore, 3GPP studies two deployment options, where each pico cell has identical cell identification (cell ID) to macro cell, and each pico cell has a distinct cell ID [11].

The intra-eNB central coordination using RRHs, as




(a) Homogenous deployment

(b) Heterogeneous deployment

**Fig. 4** Network deployments assumed in 3GPP CoMP SI.

such, enables more dynamic coordination of radio resources compared to the inter-eNB distributed coordination, which would provide higher CoMP gain. On the other hand, the RRH deployment requires high capacity optical fibers in backhaul connections, and the complexity of the central controller is increased as the number of coordinated cells/RRHs is increased. Thus, the actual number and the size of coordinated cells would be restricted by the deployment cost. Therefore, one important challenge for the CoMP investigation is to establish optimum network architectures by taking into account the trade-off between deployment cost and network capacity improvement by using relevant criteria, e.g., spectrum efficiency per cost.

## 3. Enhanced Inter-Cell Interference Coordination for Heterogeneous Deployments

Recently, the amount of mobile traffic has been increasing rapidly with the spread of high speed mobile devices such as smart phones. Therefore, further capacity enhancement in cellular networks is required. The enhancement just by increasing the system bandwidth and spectrum efficiency is not enough to meet this demand and the introduction of low power eNBs is inevitable. In the 3GPP, pico-eNBs, which are open to all the subscribers named as Open Subscriber Group (OSG) and femto-eNBs which are open to the limited subscribers named as Closed Subscriber Group (CSG), have been defined. In heterogeneous deployments where eNBs with different transmission power levels exist, new inter-cell interference issues have been found.

This section explains interference scenarios in heterogeneous deployments, the solutions for which have been specified in Release 10 and the issues to be discussed in Release 11.

### 3.1 Interference Scenarios in Heterogeneous Deployments

In LTE-Advanced SI, interference scenarios in heterogeneous deployments have been identified [3]. Figure 5 illustrates interference scenarios in a macro-femto environment. Three scenarios have been identified in LTE-Advanced SI. The first scenario is downlink interference from a femto-eNB to a macro-UE who is not a CSG member of the femto-eNB as shown in (a) of Fig. 5. The second one is uplink interference from a macro-UE to a femto-eNB as shown in (b). The third one is downlink interference from a femto-eNB to a femto-UE who is a CSG member of a different femto-eNB as shown in (c).

Figure 6 illustrates an interference scenario in a macro-pico environment. This scenario assumes downlink interference from a macro-eNB to a pico-UE at the cell edge when cell selection is based on path loss which is optimum to the uplink channel.

eICIC specifications in Release 10 focus on co-channel interference in the downlink control channel. It is because conventional interference mitigation schemes on data channels such as fractional frequency reuse (FFR) cannot be applied to the control channel due to restrictions in control signal mapping, and then the control channel capacity can become a bottleneck. For a macro-femto environment, the scenario in (a) of Fig. 5 was assumed. For a macro-pico environment, the downlink interference from the macro-eNB to pico-UE at the cell edge shown in Fig. 6 was assumed. Instead of cell selection based on path loss, that with Cell Range Expansion (CRE) [12], [13] was assumed. CRE is a technique that enhances the traffic offload by giving offset to received power from a low power eNB in the cell selection procedure. With an increase in the offset value, the possibility that a UE selects a low power eNB increases.

### 3.2 Inter-Cell Interference Coordination Techniques in Heterogeneous Deployments

In order to mitigate co-channel interference in the downlink control channel, power setting and time domain solutions [14] have been specified in Release 10 as eICIC techniques.

Power setting is targeted for mitigation of downlink interference from a femto-eNB to a macro-UE. In the case that a femto-eNB is located at the cell edge of a macro-eNB, downlink performance of the macro-UE near the femto-eNB is degraded significantly due to interference from the femto-eNB as the received power from the macro-eNB is small. Therefore, transmission power of the femto-eNB should be restricted to mitigate interference to the macro-UE. In power setting, a femto-eNB estimates its interference to a macro-UE. Then, the femto-eNB sets its transmission power so that interference to the macro-UE is sufficiently mitigated as shown in Fig. 7.

As power setting schemes, three representative examples are shown below.

1. Power setting based on the maximum received

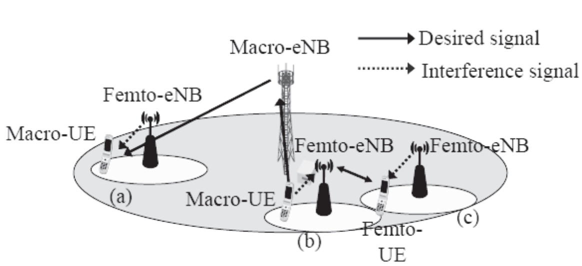



**Fig. 5** Interference scenarios in macro-femto environment.

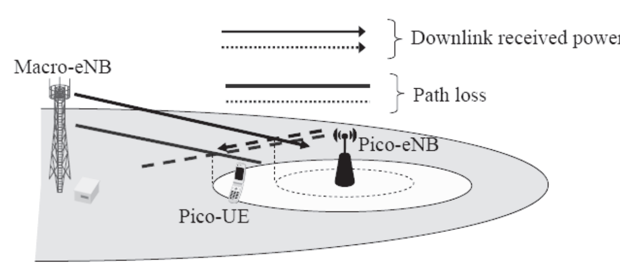



**Fig. 6** Interference scenarios in macro-pico environment.

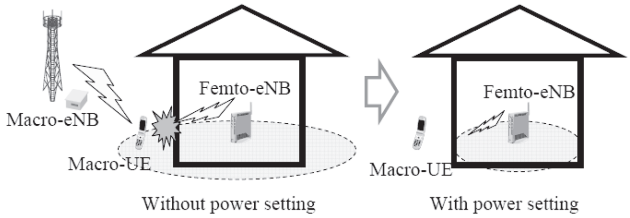



**Fig. 7** Interference mitigation by power setting.

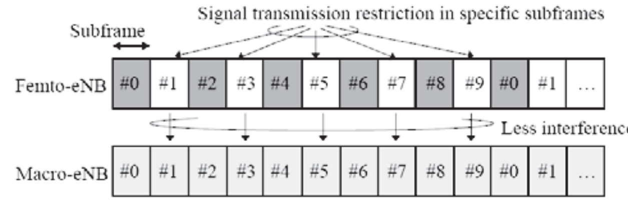



**Fig. 8** Restriction on signal transmission in time domain solution.

power of a macro-eNB at a femto-eNB [15].

2. Power setting based on path loss between a femto-eNB and a macro-UE [16].

3. Power setting based on signal to interference power ratio at a macro-UE [17].

In scheme 1, for example, a femto-eNB sets its transmission power by

$$\mathrm{Ptx} = \max(\min(\mathrm{PM} + \mathrm{Poffset}, \mathrm{Pmax}), \mathrm{Pmin}) \qquad (1)$$

where Ptx is the transmission power of a femto-eNB, PM is the received power at a femto-eNB from macro-eNB, Poffset is the fixed offset value, Pmax is the maximum transmission power of a femto-eNB, and Pmin is the minimum transmission power of a femto-eNB. As PM becomes smaller, the femto-eNB judges the macro-eNB is located further that is interference from the femto-eNB to the macro-UE is larger. Then, the femto-eNB sets its transmission power smaller.

In the case that the path loss between a femto-eNB and a macro-UE is large, interference from the femto-eNB to the macro-UE becomes smaller. However, this aspect is not considered in scheme 1 and scheme 1 may set its transmission power unnecessarily low. Therefore, the power setting in scheme 2 takes into account path loss between the femto-eNB and the macro-UE in estimating Poffset in (1), for example, by

$$\mathrm{Poffset} = \mathrm{PUL\_tx} - \mathrm{PUL\_interference} + \mathrm{P0} \qquad (2)$$

where PUL_tx is the transmission power or its estimated value of a macro-UE, PUL_interference is the measured power of uplink interference at a femto-eNB and P0 is the fixed value.

In scheme 3, for example, a femto-eNB sets its transmission power by

$$\mathrm{Ptx} = \max(\min(\mathrm{SINR\_MUE} + \mathrm{Poffset}, \mathrm{Pmax}), \mathrm{Pmin}) \qquad (3)$$

where SINR_MUE is the measured SINR at a macro-UE. This scheme can directly reflect the received signal quality at the macro-UE. However, the macro-UE cannot report its measurement results directly to the femto-eNB as such an interface has not yet been defined in 3GPP. The macro-UE can only report to the macro-eNB. Therefore, a new interface between the macro-eNB and femto-eNB to transfer the report from the macro-UE or a direct reporting scheme from the macro-UE to the femto-eNB must be newly specified to achieve this scheme.

The time domain solution mitigates interference from an eNB to another eNB by restricting the signal transmission from the eNB in the time domain.

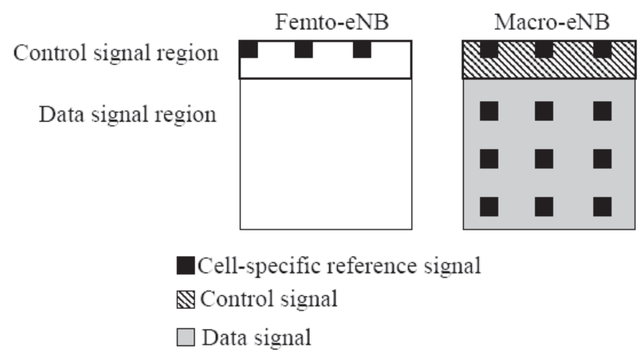



**Fig. 9** Restriction on signal transmission in MBSFN subframe.

Figure 8 illustrates an example of interference mitigation with time-domain restrictions on the signal transmission. This figure is an example for a case in which interference from a femto-eNB to a macro-UE is mitigated. Here, it is assumed that the femto-eNB and the macro-eNB are synchronized. By restricting signal transmission in specific subframes at the femto-eNB, interference to the macro-UE can be mitigated at the timing of the restricted subframes at the femto-eNB.

The configuration of Multicast/Broadcast over Single Frequency Network (MBSFN) subframes is a representative scheme to restrict signal transmission at the eNB. The MBSFN subframe was originally defined to be applied to multicast/broadcast service in LTE Release 8. It is specified in LTE Release 8 that CRSs in the MBSFN subframes are not used for UE measurement and LTE UE recognizes the position of MBSFN subframes. Therefore, signal transmission can be stopped not only for data signals and control signals but also for CRS in MBSFN subframes as shown in Fig. 9. It should be noted that MBSFN subframes can be configured only at 6 specific subframes in a radio subframe which consists of 10 subframes.

An Almost Blank Subframe (ABS) is another kind of subframe defined in Release 10 in which restriction to the signal transmission can be applied. Release 10 UEs recognize ABS but prior release UEs do not. Therefore, CRSs cannot be stopped in ABS.

In LTE-Advanced, carrier aggregation (CA) which bundles multiple LTE carriers was specified. In addition to eICIC techniques, which assume co-channel interference within one carrier, a CA-based scheme that assumes multi-

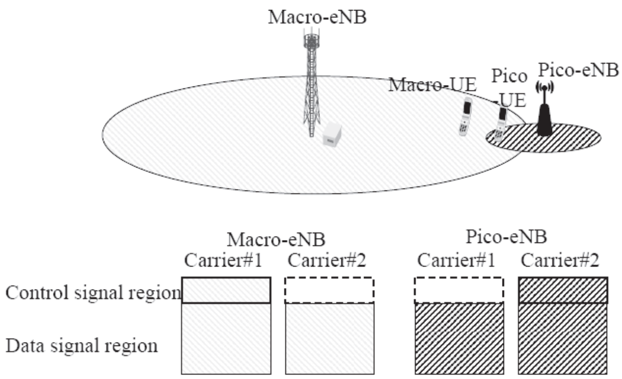



**Fig. 10** CA-based interference coordination scheme.

carrier operation has been considered in LTE-Advanced SI.

Figure 10 illustrates an example of a CA-based scheme. It is assumed here that both macro-eNB and pico-eNB utilize two carriers and each eNB utilizes different carriers for transmission of the control signal. In the control signal region of the carrier where each eNB does not transmit a control signal, each eNB does not transmit any signal or transmit a signal with low power to mitigate interference to the control signal.

In LTE-Advanced, a control channel in a carrier can indicate resource allocation information of different carriers by defining the carrier indicator field (CIF) and it enables the implementation of an interference coordination scheme across multiple carriers as shown in Fig. 10.

### 3.3 Remaining Issues in Inter-Cell Interference in Heterogeneous Deployments

In Release 11, the further enhancement or optimization of eICIC techniques will be discussed. Release 10 focused on the interference to downlink control signals. In Release 11, interference mitigation in the uplink control signal and in the data signal both for the downlink and uplink are to be considered.

## 4. Relay Transmission Techniques

Relaying has been considered for LTE-Advanced as a tool to improve the coverage of high data rates, the cell-edge throughput, and/or to provide coverage in former un-served areas. A RN is part of the radio access network and behaves similar to an eNB from the perspective of a UE. A RN has a wireless connection to a donor eNB (d-eNB) as illustrated in Fig. 11.

### 4.1 Relay Techniques Considered in Feasibility Study

Various types of relay techniques can be envisaged. Feasibility of those various candidates was studied in LTE-Advanced SI. A simple RF repeater, a so-called *amplify-and-forward* relays [18], was specified as a part of the Release 8 specifications [19]. However, it is hard to obtain a substantial improvement in coverage of the higher data rates due to their simplicity. Thus, advanced relays were considered as a potential key technology to achieve the requirements [3].

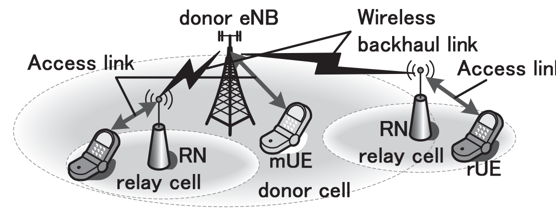



**Fig. 11** Operation principle of relaying.

#### 4.1.1 Relay Node Category

At the beginning of the feasibility study, three types of *decode-and-forward* relays, which decode and re-encode the received signal before forwarding it, were mainly considered in terms of implemented functionality at the RN.

**Layer 1 (L1) relay:** An L1 relay is an advanced repeater equipped with fast Fourier transform (FFT)/inverse FFT (IFFT) as physical layer functionality in order to perform frequency-selective relay and optimum power allocation in the frequency domain [20].

**Layer 2 (L2) relay:** In addition to the L1 relay, the L2 relay utilizes a part of the L2 functions in order to provide, e.g., cooperative transmission [21] and/or cooperative Hybrid ARQ (HARQ) retransmission between the d-eNB and RN and/or between RNs. Since this type of relay behaves as an integral part of the donor cell it does not have a scheduling function nor its own cell ID. A Hybrid of the RF repeater and L2 relay was also proposed. The hybrid RN amplifies and forwards initial data, then transmits the re-encoded initial data if re-transmission is required.

**Layer 3 (L3) relay:** In addition to the L2 relay, the L3 relay has all functionalities for the radio resource management (RRM) from the perspective of a UE. Thus, a L3 relay has its own cell ID and controls its own cell, each of which appears to a UE as an individual cell distinct from the donor cell.

One of the most important requirements in the development of a Release 10 relay is to support legacy UEs (i.e. backward compatibility), that is, the RN behaves as an eNB accommodating Release 8 UEs. This ensures gradual introduction of relay cells into existing networks. Taking the compatibility, the expected performance improvements and required additional specification efforts into account, the L3 relay was selected as the relay architecture for Release 10.

#### 4.1.2 Band Assignment between Backhaul and Access Links

Since the RN communicates with both d-eNB and UEs belonging to the RN (rUEs) avoidance of self-interference from transmission to reception between the backhaul link and the access link of the relay cell has to be addressed by a reasonable method. Therefore, the time, frequency or spatial isolation between the backhaul and access links can be considered. In the following, the access link indicates the link between the RN and rUE unless explicitly stated.

For LTE-Advanced, outband and inband relay operations were defined with respect to the resource isolation between the backhaul and access links [3].

- **Outband relay:** A frequency band assigned to the wireless backhaul link is distinct from that assigned to an access link. Consequently, full duplex relay operation can be achieved.
- **Inband relay:** The wireless backhaul link shares the same frequency band used by the access link within the cells belonging to a d-eNB.

An outband relay can be achieved as an implementation detail by reusing Release 8 radio interface (between eNB and UE) for the backhaul link, while the realization of an inband relay requires careful consideration in terms of backward compatibility to LTE Release 8. In Release 10, time domain separation between backhaul and access links was introduced to achieve inband relay operation. The following section describes this in detail.

### 4.2 Relay in LTE-Advanced

As mentioned above, Release 10 relays support basic L3 relay functions with backward compatibility to Release 8 UEs [22]. RNs are expected to be stationary, i.e., mobility of RNs is not assumed. Each RN is connected to a predefined d-eNB. The number of hops for relaying was limited to two, i.e., one hop as the backhaul link and one hop as the access link.

#### 4.2.1 Protocol Architecture

A RN is connected to a d-eNB via the Un interface, and UEs connect to the RN via the Uu interface as shown in Fig. 12, where the Evolved Packet Core (EPC) is the evolved core network (CN) connected to Release 8 and later releases of LTE, and S1 is the interface between eNB/RN and EPC [23]. To avoid or minimize the impact to the existing UEs and EPC from relay introduction, on the Uu interface, all control plane and user plane protocols are terminated in the RN namely the RN behaves as an eNB from the UE perspective. For the Un interface, the RN has an S1 interface and behaves as an eNB from the EPC perspective because the eNB acts similar to an S1 proxy.

#### 4.2.2 Resource Partitioning for Backhaul Link

Time division based resource partitioning at the RN is supported to enable the inband relay operation as shown in Fig. 13. Backhaul and access links are allocated to different subframes in the same frequency bands for each uplink and downlink (half duplex). In addition, for TDD, downlink and uplink transmissions on the backhaul link are performed in the DL and UL subframes at the d-eNB, respectively. These aspects allow the sharing of radio resources in the same subframe between backhaul links to RNs and access links to UEs belonging to an eNB (mUEs).

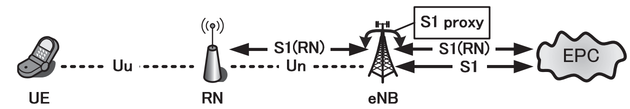



**Fig. 12** Relation between nodes and interfaces.

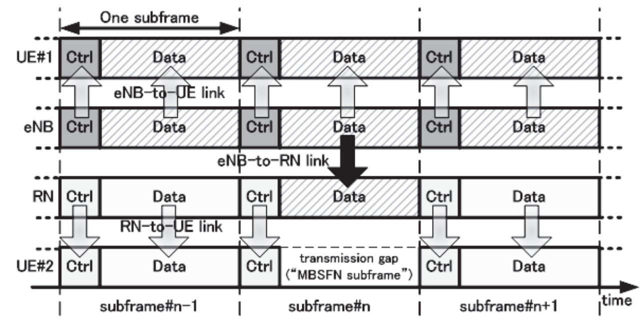



**Fig. 13** Resource partitioning and MBSFN subframe usage.

To provide the time division resource partitioning between backhaul and access link transmissions in the downlink, i.e., to create "gaps" in the access link transmission, configuring MBSFN subframes in the access link has been adopted as a way to notify the rUEs (including Release 8 UEs) that such subframes contain, e.g., the PDCCHs, CRSs only in the first one or two OFDM symbols but do not contain any PDSCHs or CRSs in the following OFDM symbols as illustrated in Fig. 13. Moreover, because Release 8 UEs do not carry out the measurement using CRSs in the MBSFN subframes except on the first two OFDM symbols, the gap can be made in the access link without breaking the channel quality measurement of Release 8 UEs. In the uplink no special treatment is required because the RN just does not allocate access link resources for uplink subframes where it intends to transmit to the d-eNB.

#### 4.2.3 Downlink Channel Structure for Relay

To support Release 8 UE association to a RN, i.e., backward compatibility, PDCCHs that are allocated to the first one, two, or three OFDM symbols must be transmitted in all subframes on the access link. Therefore, an RN cannot receive all or a part of the OFDM symbols containing PDCCH on the backhaul link. Consequently, the Relay-specific PDCCH (R-PDCCH) was newly defined and it is transmitted inside the PDSCH region in backhaul subframes.

The RN decodes downlink resource allocation signaling (DL grant) and uplink resource allocation signaling (UL grant) in the R-PDCCH, and then receives the PDSCH and

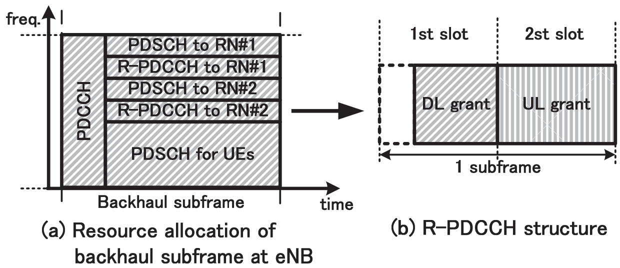



**Fig. 14** R-PDCCH multiplexing and structure.

transmits the physical uplink shared channel (PUSCH) corresponding to the DL grant and UL grant, respectively. The DL grants are transmitted only in the first slot and the UL grants are transmitted only in the second slot, as shown in Fig. 14. This is intended to shorten the processing time to enable early PDSCH demodulation, which affects the implementation complexity.

Two R-PDCCH transmission methods are defined.

- **Without cross-interleaving:** A single R-PDCCH occupies dedicated frequency resource(s) and can support single rank beamforming by utilizing the DM-RS explained in Sect. 2.2.
- **With cross-interleaving:** Several R-PDCCHs are interleaved in the frequency domain. This mode is suited to obtaining the frequency diversity gain in the case that a relatively large number of RNs is associated with a d-eNB, or in the case that the d-eNB cannot accurately predict which frequency resources are most suitable for the R-PDCCH transmission.

#### 4.2.4 Hybrid ARQ Operation

For the access link, HARQ operation specified in Release 8 is reused without any modification to retain backward compatibility. Meanwhile, for the FDD system, MBSFN subframes cannot be configured in subframes #0,4,5, and 9 in a frame (10 ms) while the HARQ round trip time is 8 ms. Therefore, a backhaul link specific HARQ operation was introduced that retains the principle of Release 8 HARQ operation as much as possible. For TDD, the HARQ round trip time is 10 ms so that no special handling is required.

### 4.3 Cooperative Operations for Relay Enhancement

The following part describes several coordination schemes for relay enhancement. Some of these schemes were also considered in LTE-Advanced SI.

**Network cording:** The network coding scheme was proposed to conserve forwarding resources [24] and was proposed in LTE-Advanced SI. In the proposed network coding scheme, the downlink signal from the d-eNB and the uplink signal from a UE are XOR-ed by signal to both the UE and the d-eNB. However, it was not applicable to the LTE system due to the difference between the existing downlink and uplink frame formats, that is, the introduction of this scheme would require a modification of one or both formats. Consequently, this approach cannot satisfy the backward compatibility requirement.

**Resource management:** To improve the overall system capacity in relay systems, several papers have investigated radio resource management schemes for backhaul and/or access links [25]–[27]. Time domain resource allocations among access and backhaul links for LTE-Advanced relay system were investigated in [25]. This paper shows based on simulation results that the number of backhaul subframes that achieves the maximum throughput is dependent on the number of RNs per d-eNB. Frequency domain resource partitioning among access and backhaul links was studied in [26], [27]. These papers reveal that resource partitioning improves both the system capacity and the cell edge user throughput performance. However, for LTE-Advanced relay, frequency domain resource partitioning is only achieved in the transmission band domain, i.e., as an outband relay, to establish resource isolation between the backhaul link and the access link.

**Interference coordination:** Inter-cell interference (ICI) coordination is also an important technique to improve system performance. The resource partitioning can also be applied for ICI mitigation [28], [29]. These show that coordinated resource partitioning can mitigate ICI among macro cell and relay cells and that it leads to improvement in the system performance, especially for the cell edge user throughput. ICI mitigation based on backhaul subframe coordination was also investigated [30].

**CoMP and eICIC application:** LTE-Advanced relay was designed with full L3 functionality and behaves as an eNB from the UE perspective. Therefore, CoMP and eICIC techniques described in the previous sections can also be applied to the RN to improve the system capacity and the cell edge user throughput.

## 5. Conclusion

This paper presented an overview of radio interface technologies for cooperative transmission in 3GPP LTE-Advanced, i.e., CoMP transmission, eICIC for heterogeneous deployments, and relay transmission techniques. They are emerging techniques associated with enhanced network deployments that had not been considered when LTE initial release (Release 8) was specified. In the 3GPP, standardization efforts toward further enhancing the LTE radio interface are continuing so that we can meet the future traffic demand, which is rapidly growing.

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