UE's Role in LTE Advanced Heterogeneous Networks

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ABSTRACT

Deployment of low-power nodes such as picocells, femtocells, and relay nodes within macrocell coverage is seen as a cost-effective way to increase system capacity and to equip wireless WANs with the ability to keep up with the increasing demand for data capacity. These new types of deployments are commonly referred to as heterogeneous networks and are currently receiving significant attention in industry. However, simple deployment of low-power nodes can lead to underutilization of air-interface resources due to the relatively small footprint of the low-power nodes or service outage in the case of femto cells with restricted access. Time-domain interference management techniques by the configuration of almost blank subframes, introduced in LTE Rel-10 standards, allow the removal of most of the interference from the dominant interfering nodes. This mechanism enables cell biasing or cell range extension of weak cells, thereby maximizing the incremental gain provided by the deployment of low-power nodes. The configuration of ABS changes the interference conditions seen by the user equipment and therefore requires corresponding resource-specific measurements and feedback at the UE. In this article, we provide an overview of LTE Rel-10 resource specific radio link monitoring, radio resource management, and channel state information feedback procedures. Also, we provide evaluation results to show that UE receivers, in the detection of weak cells and removal of interference in demodulation of control and data channels, play a critical role in realizing the full potential that the deployment of heterogeneous networks can offer.

INTRODUCTION

Release 10 (Rel-10) standards of Long Term Evolution (LTE) fourth-generation (4G) mobile communications, referred to as LTE-Advanced, have recently been completed by the Third Generation Partnership Project (3GPP) standards body. Since the first release (Rel-8, introduced in 2008 [1]), new features have been added, and one of the key enhancements in LTE Rel-10 [2] is the adoption of enhanced intercell interference coordination (eICIC). The main driver behind adoption of eICIC in LTE Rel-10 was to ensure reliable LTE operation in heterogeneous network deployments.

In heterogeneous networks, low-power nodes such as picocells, femtocells, and relay nodes are deployed within macrocell coverage; accordingly, the node density in the macro cell area increases. These types of deployments can offer substantial increase in data capacity by offloading traffic from the macrocell to the low-power nodes along with full reuse of frequency resources across all the cells. With the sharp increase in data demands in cellular networks due to the popularity of smart mobile devices, these new types of deployments utilizing low-power nodes are receiving significant attention in industry as a promising and cost-effective way to boost the system capacity [3, 4].

However, large gains cannot be achieved just by the deployment of heterogeneous networks, but require that enhanced interference management techniques be applied in the network. This is because the interference condition in heterogeneous networks becomes much more hostile than in traditional homogeneous cellular networks, and it is more likely for the user equipment (UE) to experience severe interference, especially from a neighbor cell covering the same area as the serving cell of the UE. Moreover, simple deployment of low-power nodes can lead to underutilization of air-interface resources due to the relatively small footprint of the low-power nodes when compared to macro nodes, and service outage of the macrocell UE within coverage of femtocells with restricted access [5–8]. For that reason, cell biasing techniques, also referred to as cell range expansion (CRE), are commonly utilized to direct traffic to underutilized cells, which further exacerbates the interference problem. The interference issues can severely limit the capacity improvement achievable by the deployment of heterogeneous networks.

In order to address the challenges that introduction of heterogeneous networks creates, time-domain eICIC techniques to effectively coordinate interference from the dominant interfering cells were adopted in LTE Rel-10. The LTE Rel-10 eICIC techniques enable interfering cells to configure subframes with almost no transmissions, referred to as almost blank subframes (ABS). The configuration of ABS is passed to neighboring cells via an X2 interface [9] or an operation, administration and management (OAM) interface. Then UE under harsh interference conditions can be served in the ABS by their respective serving cells.

With the configuration of ABS, UE processing needs to be extended compared to the UE served in traditional cellular networks in order to fully achieve the capacity increase enabled by the heterogeneous networks. As the configuration of ABS can cause interference to significantly vary from one subframe to another, for UE under potentially severe interference it is necessary to configure resource-specific channel measurements and feedback. By limiting the measurements to the protected subframes, LTE Rel-10 networks and UE support procedures enabling biased handover decisions by providing adequate radio resource management (RRM) measurement reporting and channel state information (CSI) feedback without risking radio link failure at the UE.

Another important role of the UE in LTE heterogeneous networks is to cope with interference, which is not completely avoided by the configuration of ABS. Reference signals for channel quality measurement and demodulation, and cell acquisition signals must be transmitted on a predetermined schedule from all base stations and thus even in ABS to fully support legacy terminal operation. These signals are transmitted at high power in general; moreover, the experienced interference level at the UE becomes much worse with an increase in coverage of low-power nodes considering the configuration of ABS. As shown in the following sections, cancellation of interference due to those signals at the UE plays a critical role in realizing the full potential of heterogeneous networks.

The article is organized as follows. Deployment scenarios of heterogeneous networks are discussed. Interference coordination techniques, and UE measurement reporting and CSI feedback mechanisms adopted in LTE Rel-10 are explained. We present link and system performance results, highlighting the importance of UE's roles. Trends for future research are given, and conclusions are drawn.

Deployment Scenarios

Mobile wireless industry has grown rapidly in the past two decades. The increased adoption of data-intensive mobile devices (e.g., smart phones, notebooks and tablets) has further accelerated network capacity demands. Furthermore, data traffic in general is not evenly distributed over the network; most of the traffic is heavily concentrated in certain areas at selected periods of time. The wireless network capacity has improved through access technology evolutions from circuit to packet switching, from single-dimension frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA) to fine-granularity multidimensional 4G orthogonal FDMA (OFDMA) technologies. To further increase the network spectral efficiency and support manifold (10 or more times) capacity growth, an innovative way to grow multitier dense heterogeneous mobile wireless networks is needed to fully exploit macro-, micro-, and picocells as well as femtocells and WiFi nodes.

The major drivers for heterogeneous networks are dense urban sites below rooftops, stadiums, hotspots, and coverage holes. Figure 1 illustrates potential deployment scenarios for low power nodes.

In Fig. 1, the following scenarios are identified:

- Dense urban low-power nodes support high traffic demands in dense downtown buildings with indoor and outdoor pedestrians. Radio nodes on the street level with innovative installation, such as traffic lights, are needed since addition of traditional macrocells is not feasible.
- Stadiums and airports are characterized by extreme user densities. Coordination of the transmission and resource management among those radio nodes minimizes interference, and maximizes the network capacity and user performance.
- Hotspots, at shopping centers and local colleges, require smooth handover and traffic distribution among macr and small cells.
- Lowpower low-cost radio nodes also make filling coverage holes more economically viable.

Interference management is crucial for dense urban and hotspot traffic scenarios. The sites are typically under good macrocell coverage with short intersite distance. This creates a strong imbalance between uplink and downlink coverage. Therefore, interference management and cell range expansion becomes important to enable capacity gain and user connectivity around the cell boundary of various heterogeneous network nodes. The power of those small cells could range from 250 mW to 5 W for outdoor units, or even down to 50 mW for indoor femtocells, compared to a traditional macrocell with 40 W transmit power per antenna. Therefore, low-power nodes are, from both the size and weight perspectives, only a fraction of a macrocell. Hence, those small cells could easily be mounted on a light pole, on traffic lights, or even on a power line or cable. In addition, user deployed home cells may be configured with restricted access.

The key performance metrics for such heterogeneous network are overall network throughput performance, cell edge performance and in-building performance as well as seamless mobility. Maximal gain would be achieved if we could adequately adjust UE association with various cells, and manage radio resource and interference accordingly.

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Heterogeneous network deployments can yield severe interference conditions where a dominant interferer prevents some UE from establishing and maintaining reliable communications with their corresponding serving cells.

Figure 1. *Deployment scenarios for lower-power nodes: a) dense urban; b) stadium; c) hotspots; d) coverage holes.*

LTE supports flexible and fine granularity of time, frequency, and power allocation across radio resources. Low-power cells can be deployed where traffic is generated and support radio resource when the traffic is demanding. Sophisticated interference management will ensure overall network capacity, UE performance, and service connectivity.

Interference Coordination

Heterogeneous network deployments can yield severe interference conditions where a dominant interferer prevents some UE from establishing and maintaining reliable communications with their corresponding serving cells. There are two identified scenarios that create such harsh interference conditions:

- Macro eNB — Pico eNB deployments with CRE, where UE in a CRE area experience harsh interference conditions
- Macro eNB — Closed subscriber group (CSG) home eNB (HeNB), or CSG-CSG HeNB deployments, where an HeNB with a CSG access creates a coverage hole in their vicinity for non-member UE.

Macro-Pico Deployments with UE Operating in Cell Range Expansion

Deployment of small open access cells, referred to as picocells, does not create coverage holes like CSG HeNBs. Due to non-restricted access, in theory, UE should always be associated with a cell with good signal-to-interference-plus-noise ratio (SINR). However, in practice, UE association with a cell with the highest received SINR may not always be desirable or, in some cases, feasible.

Load Balancing — System performance can be significantly improved if UE were served by weak picocells on resources vacated by the macrocell. This technique is referred to as CRE for load balancing purposes and is illustrated in Fig. 2, where the cell to serve UE is chosen taking into account the number of UE being served by the respective cells as well as the SINR. This is mainly because:

- More UE can connect to the picos and take advantage of the spectrum offered by the picos.
- Multiple picos can reuse the resources vacated by the macro, allowing for the cell-splitting gains.

Similar arguments apply to low-power relay nodes as well, but the performance trade-offs may be different due to the existence of resources used in supporting wireless backhaul between macro and relay nodes.

Mobility Considerations — Deployment of picocells and relays creates smaller cells where interference characteristics change more rapidly than in a homogeneous network consisting of macrocells only. As a consequence, handover frequency is expected to increase, potentially increasing instances of radio link failure (RLF) and even undesirable transition to idle state without RRC connection. In this scenario, CRE can be utilized to reduce frequency of handovers. For example, high-mobility UE may not be handed over to picocells, as shown in Fig. 3. The network can utilize CRE and serve high-mobility UE on the macrocells only, while handing over low-mobility UE to the pico eNBs.

Macro-CSG or CSG-CSG Deployments

Figure 4 illustrates a severe interference scenario in relation to CSG HeNB deployments. It

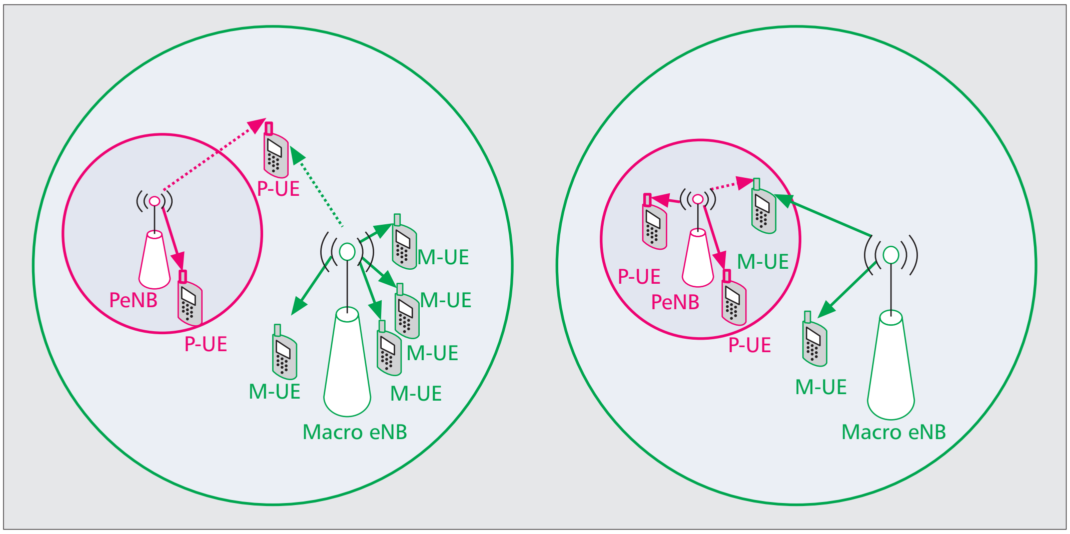

Figure 2. *Macro eNB–pico/relay eNB load balancing.*

presents a case where UE is not a member of the CSG of an HeNB, but is located close to the HeNB. There are two scenarios that create severe interference:

- Downlink: *Macro UE is being jammed by an HeNB*. HeNB power control [7, 10], with or without macro UE assistance, can reduce the frequency of the occurrence of severe interference, but typically large outage is still commonly observed.
- Uplink: *An HeNB is being jammed by macro UE*. Since macro UE is power controlled by the macrocell, macro UE will cause strong, likely bursty interference to the HeNB. Noise padding can smooth out interference, but it also decreases capacity at the serving HeNB, and increases interference to the neighboring HeNBs and macro network. If the macro UE is closer to the HeNB than the UE served by the HeNB, noise padding cannot solve the problem, and UE served by the HeNB would experience outage.

The interference conditions can be so severe as to completely desensitize the corresponding receiver, that is, the macro UE in the vicinity of the HeNB on downlink, or the HeNB on uplink.

While Fig. 2 illustrates a scenario in which the interference conditions are between the macro eNBs and the pico eNBs, it is easy to see that similar dominant interference conditions, as shown in Fig. 5, can occur between HeNBs. In this case, the UE is in the coverage of an HeNB with restricted access, but it belongs to a subscriber group of a different HeNB from which the signal is weaker.

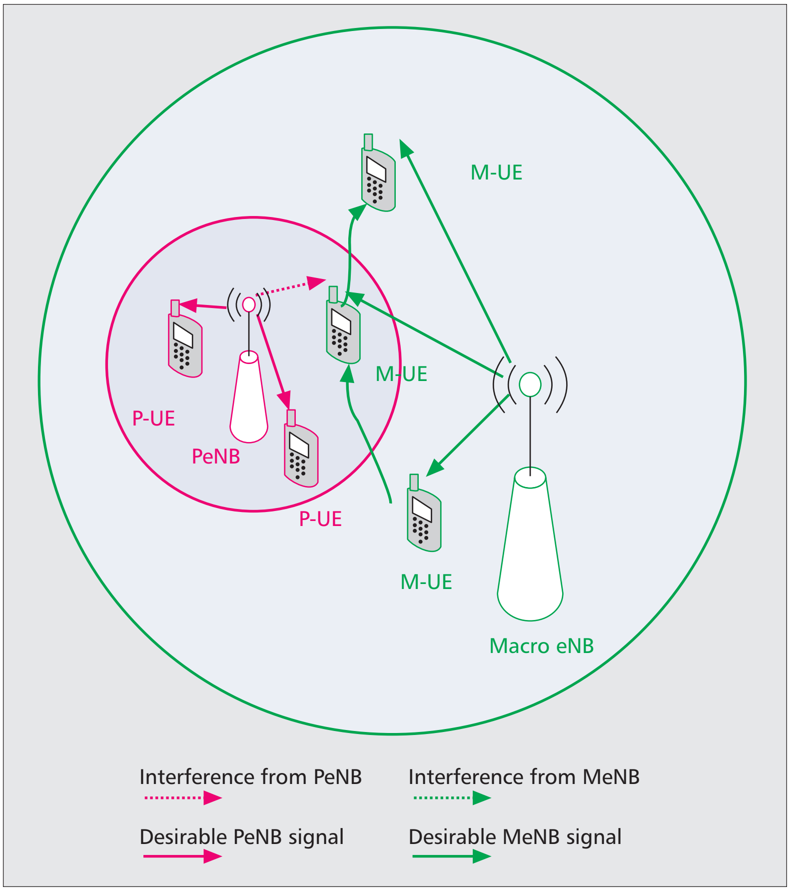

Figure 3. *Macro eNB–pico/relay eNB mobility considerations.*

Enhanced InterCell Interference Coordination

The SINR distributions in heterogeneous networks can be substantially different from the distribution in macro networks and with potentially significant numbers of UE under very harsh interference conditions. Simple power boosting and beamforming from the serving cell can improve the SINR of the downlink data channel, but cannot fully mitigate such harsh interference. Moreover, the downlink control channels and downlink acquisition signals and channels cannot utilize beamforming techniques and have stringent detection requirements. For that reason, eICIC has been introduced to provide interference management, and the eICIC technique adopted in LTE Rel-10 allows the UE to reliably receive and decode the downlink data and control channels, avoiding harsh interference from other cells in heterogeneous networks. Perfor-

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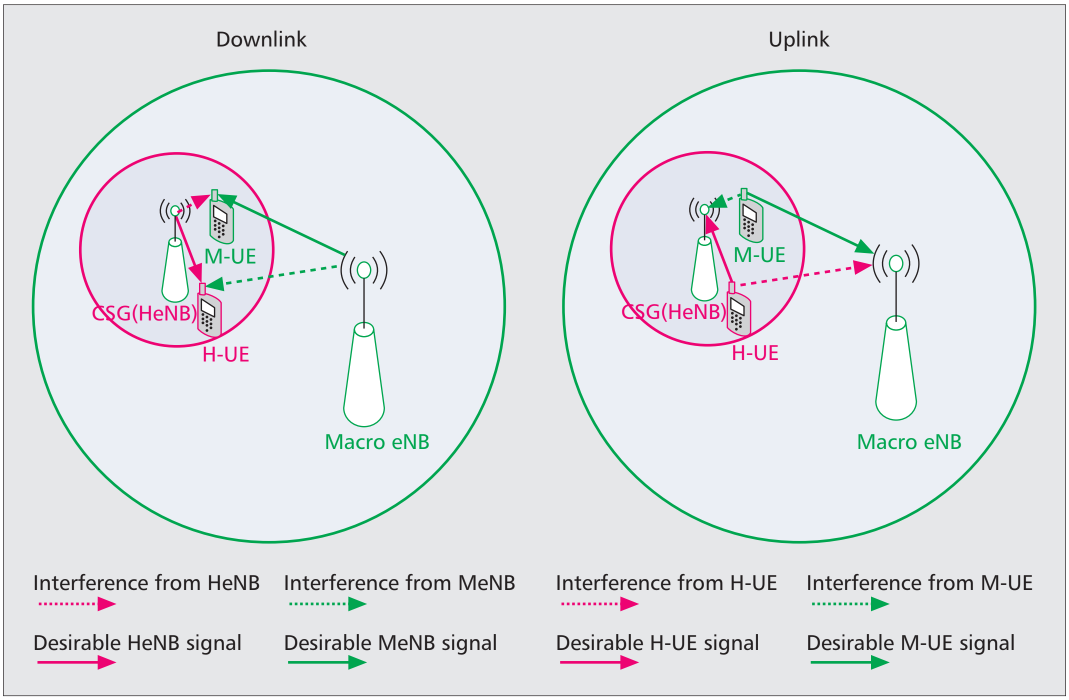

Figure 4. *Macro eNB–HeNB interference conditions.*

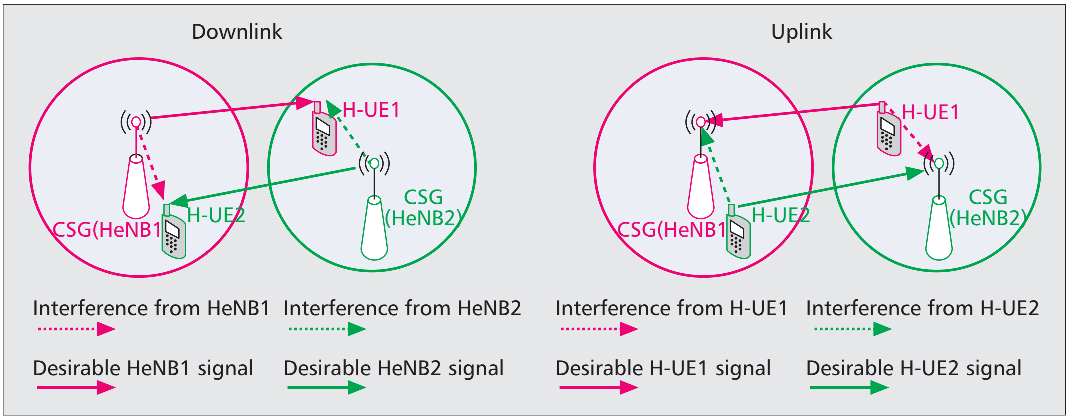

Figure 5. *HeNB–HeNB interference conditions.*

mance of the data and control channels, and also that of the acquisition signals and channels can be further enhanced by UE-based operations for interference mitigation on top of the eICIC technique, as shown later.

The interference management technique introduced in LTE Rel-10 is realized in a form of a subframe resource give-away from the dominant interfering cell so that an "interference-free tunnel" of communication can be established between the serving cell and the UE. The subframes an eNB gives away to create this "interference-free-tunnel" are referred to as *almost blank subframes*. They are referred to as "almost blank" since even though the intention is to eliminate interference on these subframes, in order to support the legacy mode of operation, acquisition signals and channels, reference signals, and system broadcast still need to be transmitted on the predetermined schedule from all eNBs regardless of whether the corresponding subframes are intended for the creation of the interference-free-tunnel or not. Uplink data transmissions are slaved to the downlink control channels; hence, partitioning of downlink resources translates to the uplink transmissions too, which can address the uplink interference problems mentioned above. Figure 6 is an exemplary illustration of the interference management technique with the resource partitioning. The macro eNB gives away subframes 1, 5, 9, 3, 7 (from left to right) to create the interference-free-tunnel, and the picocell can safely serve its UE in those subframes for data transmission in downlink and uplink. Note that the network should carefully select the resource partitioning pattern or order to enable reliable reception of system information with fixed transmission schedule and paging for UE in a CRE region.

Figure 7 illustrates downlink LTE subframes for two common reference signal (CRS) ports [1]. As can be seen from the figure, even in the absence of the scheduled downlink traffic, downlink acquisition signals and channels and CRS can create significant interference, which can be mitigated by the UE. Coordinated use of ABS among eNBs is negotiated over the backhaul link in case a low-power node has unrestricted access. Otherwise, if the access is restricted, an ABS pattern is configured by the OAM module.

MEASUREMENTS REPORTING AND CSI FEEDBACK

Meaningful communication between the network and UE starts with the acquisition of the cell candidate to become the serving cell of the given UE. Primary and secondary synchronization signals and a physical broadcast channel are utilized for cell detection and acquisition, and a common reference signal is utilized for measurements. Once the cell is detected, measured, and reported, the network can determine whether to make it the serving cell of the given UE. There is no special mechanism that, first, would enable the detection of very weak cells and, second, would grant the possibility to establish and maintain a meaningful communication link (i.e., with reliable control and data reception at the UE receiver).

The detection of weak cells can be done at the UE utilizing interference cancellation techniques. No special action by the network is required, other than synchronization among eNBs in order to create structured interference that can be exploited by the interference-cancellation-capable receiver. Performance of the interference cancellation receiver for the acquisition signals and channels is discussed further below. When actively exchanging data with the network (in RRC_CONNECTED state), UE needs to perform measurements and reporting procedures in order to ensure that proper connection with the network is maintained and the network can adequately schedule data to and from the UE.

The radio link monitoring (RLM) procedure consists of the serving cell signal quality measurements, and it determines UE behavior when radio conditions with the serving cell become unsatisfactory. At that point UE is allowed to autonomously select a new cell that is most suitable for service. Otherwise, if the radio conditions are satisfactory, UE is not allowed to autonomously select a new cell. In Rel-8, the RLM procedure was designed mainly for stationary interference; hence, UE did not differentiate among different sets of subframes. When time domain partitioning was introduced in Rel-10, this assumption did not hold anymore, and it became necessary to modify the procedure.

Radio resource management measurements and reporting, and CSI feedback procedures enable the network to obtain information about the current radio conditions at the UE. For example, the reference signal received power (RSRP) measurement is a type of RRM measurement that provides information on the signal strength of the serving and neighboring cells, and is utilized to facilitate handover. CSI feedback provides serving cell channel quality and potentially spatial channel indication that can be utilized at the eNB scheduler to select a proper

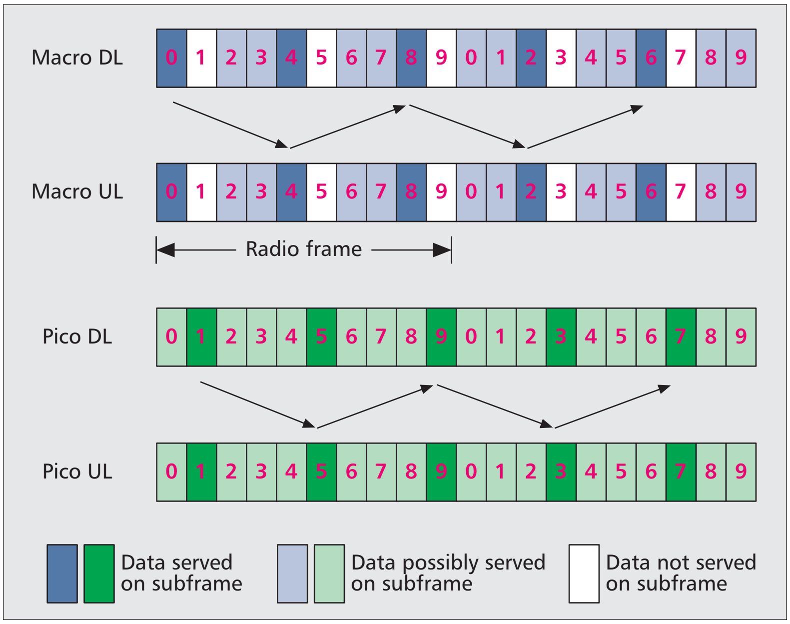

Figure 6. *Resource partitioning between macro- and picocells for eICIC.*

modulation and coding and precoding scheme. Similar to the RLM procedure, RRM and CSI feedback were also impacted by the introduction of time domain partitioning. Accuracy of RSRP measurements could have been compromised if the UE was performing measurements on non-protected subframes. CSI feedback was compromised as well as it would not be clear to the network if the UE was reporting radio conditions for interference protected or non-protected subframes.

REL-10 RLM/RRM MEASUREMENTS PROCEDURE

As mentioned above, the time domain approach adopted for eICIC introduced potentially significant interference variation from one subframe to the other. The variation of interference would be particularly pronounced for UE in the vicinity of CSG HeNBs and UE operating in a CRE region. Without subframe-specific measurements, by averaging radio conditions over all subframes, the UE would, in many scenarios, falsely detect poor radio conditions, declare RLF, and effectively not be able to maintain connection with the network. The subframe-specific RLM/RRM measurement procedure represents a core performance requirement for eICIC, and the subframe measurement pattern is signaled to the UE.

The subframe pattern for the serving cell measurements is included in the `RRCConnectionReconfiguration` message that is used to configure radio resources after RRC connection is set up when UE transitions from RRC_IDLE to RRC_CONNECTED states, or to reconfigure radio resources at any point afterward. The RLM procedure is very similar to the procedure when the subframe pattern is not configured. UE is required to assess radio link quality, effectively SINR measured on CRS, every radio frame and compare it against the thresholds Q_{out}

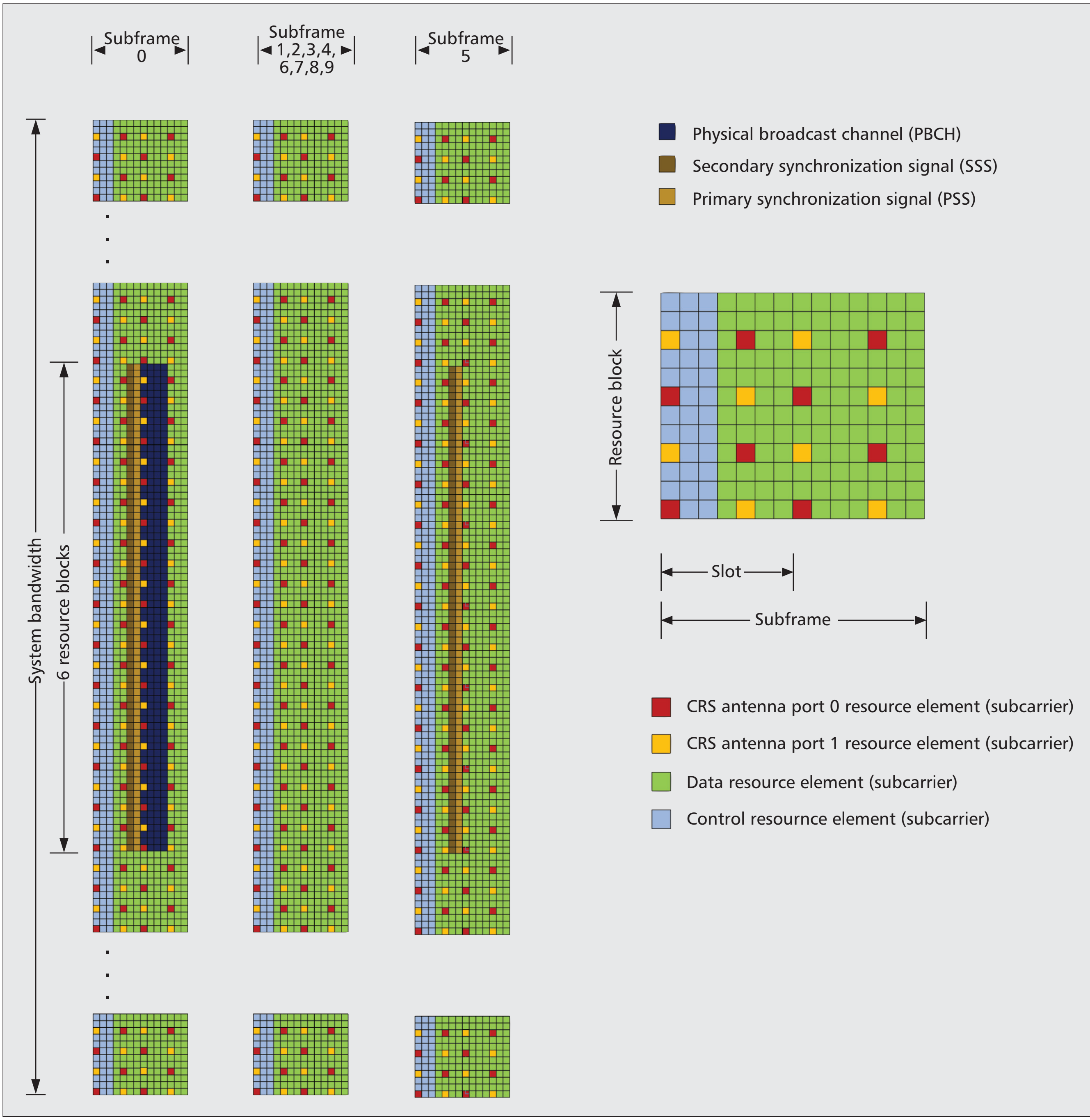

Figure 7. *Illustration of downlink LTE subframes.*

and Q_{in}. The only difference is that the measurements need to be constrained within the configured subframes. The rest of the procedure is identical. If the assessed radio link quality is worse than the threshold Q_{out}, an out-of-sync primitive is passed to the higher layers, while if the radio link quality is better than the threshold Q_{in}, an in-sync primitive is passed to the higher layers. Upon detecting the configured number of consecutive out-of-sync primitives, the UE starts a timer. If the timer expires, the UE is allowed to perform a cell selection procedure and an RRC connection reestablishment procedure on the selected cell. However, while the timer is running, the UE continues to assess radio link quality, and if a configured number of consecutive in-sync primitives is passed to the higher layers, the UE must remain connected to the serving cell and stop the timer.

The same subframe pattern is also utilized to perform RRM measurements of the serving cell. The RRM measurements consist of RSRP and reference signal received quality (RSRQ) measurements. The RSRP measurements only include the signal strength measurement of the CRS and therefore are not dependent on the subframe pattern. However, interference can become harsh on certain subframes, especially those not protected by the interference-free-tunnel. It is desirable to restrict RSRP measurements to subframes with reasonably good SINR, which ensure sufficient measurement accuracy and are also preferred to serve UE with traffic data without severe interference. The RSRQ measurement is defined as RSRQ = RSRP/RSSI, where RSSI corresponds to carrier received signal strength indicator, and RSRQ measurements can significantly vary from subframe to subframe as RSSI includes the total E-UTRA carrier strength, which includes both the desired signal and interference. In order to report correct measurement values, UE needs to restrict its measurements to the signaled set of subframes.

UE is configured to report RSRP, RSRQ, or both. In addition to the subframe pattern for the measurements of the serving cell, the pattern for the neighboring cells can be included as well. If not included, UE can treat all subframes equally when performing measurements. In a common implementation with cell biasing for macro/pico deployments, a macro eNB would utilize ABS to provide an interference-free-tunnel for pico UE, and a pico eNB would utilize all subframes by using the subframes not protected by the interference-free-tunnel in serving UE located near the picocell center. In this scenario, UE would be configured to perform unrestricted measurements of the serving cell when served by macro eNBs and restricted measurements of the serving cell when served by a pico eNB. Measurements of the neighboring cells would always be restricted since in order to be able to measure weak cells. UE measurements need to be done on ABS of the macro eNB regardless of whether the UE is served by a macro or pico eNB.

REL-10 CSI FEEDBACK PROCEDURE

Similar to RLM/RRM measurements, CSI measurements also need to be restricted if cell biasing is utilized due to either CRE or deployment of CSG eNBs. Accurate measurements of the channel and interference are critical for scheduling efficiency; therefore, it is desirable to configure restricted measurements whenever restricted measurements for RLM/RRM are needed because of either CRE or deployment of CSG HeNBs.

CSI feedback is configured through an `RRC-ConnectionReconfiguration` message. Similar to restricted RLM/RRM measurements, restricted CSI measurement configuration is optional. If restricted CSI feedback is configured, there are two sets of subframe patterns signaled to the UE. These two sets are disjoint, and the union of the two sets does not need to add up to all subframes.

In periodic reporting, physical uplink control channel (PUCCH) resources for CSI feedback are explicitly linked to either the first or second set. Linking between the configured subframe sets and CSI feedback for aperiodic reporting is, however, implicit. If restricted sets are configured, and the trigger for an aperiodic report falls within a subframe that is a member of a particular set, UE computes CSI feedback to represent the radio conditions within the corresponding set. The CSI measurements consist of channel and interference measurements. In order to ensure proper UE feedback, it is necessary to ensure restricted measurements, at least for the interference part.

LINK PERFORMANCE

As discussed earlier, ABS are utilized to create the interference-free-tunnel and enable CRE of weak cells. However, configuration of ABS does not provide interference coordination mechanisms for all cases of interest. For example, configuration of ABS combined with subframe shift between macro- and picocells is feasible for some scenarios in case of frequency-division duplex (FDD) operation, and can provide improved detection of acquisition signals and channels. However, subframe shift is not feasible for time-division duplex (TDD) operation and may not always be desirable for FDD systems either. The acquisition signals and channels need to be transmitted on a fixed schedule, and an interference cancellation receiver can be exploited to suppress interference at the UE, especially in synchronous deployments when they "collide" in time and frequency. In addition to the performance of the acquisition signals and channels, in this section we evaluate performance for the downlink control and data channels. Fully synchronous network deployment is assumed.

DETECTION OF ACQUISITION SIGNALS

The very first requirement to establish a communication with a cell is to detect the cell. Cell acquisition relies on cell identification by the detection of the physical cell ID (PCI) using primary and secondary synchronization signals (PSS/SSS) and decoding of the physical broadcast channel (PBCH) to identify the most important system parameters, such as transmission bandwidth, physical hybrid automatic repeat request (HARQ) indicator channel (PHICH) information, and the number of transmit antennas, which is necessary to decode downlink control channels and system information.

Table 1 shows PSS/SSS (cell ID) detection probability for a system with a serving cell carrier over thermal noise, carrier-to-noise ratio (C/N) = 0 dB in the presence of a single strong interferer with interference over thermal noise, and interference-to-noise ratio (I/N) = 20 dB with the full collision of PSS/SSS sent by the serving and interfering cells. The results are for a typical urban channel profile at UE speed of 30 km/h and 2 GHz carrier frequency (ETU30) [11]. 0 Hz frequency offset is assumed. The results in Table 1 show that detecting cells in the presence of a strong interferer is feasible. For the considered scenario, the effective SINR is –20 dB. For a typical Rel-8 UE receiver without interference cancellation, cell detection is not practically feasible if the interferer is more than 9 dB stronger than the serving cell.

Table 2 shows required C/N levels for 1 percent PBCH decoding probability for a 2 Tx and 2 Rx antenna system in the presence of an interferer at I/N = 16 dB with full collision of PBCH and 4 bursts combined at the receiver. The results are also for ETU30, where 0 Hz frequency offset is assumed.

Results in Table 2 show PBCH performance in the presence of a strong interferer. Block error rate (BLER) = 1 percent is obtained for an effective SINR of –10.5 dB without interference suppression and –18.8 dB with PBCH inter-

Accurate measurements of the channel and interference are critical for scheduling efficiency; therefore, it is desirable to configure restricted measurements whenever restricted measurements for RLM/RRM are needed because of either CRE or deployment of CSG HeNBs.

Similarly to PCFICH, PHICH performance for the interference cancellation receiver would be robust against network planning, i.e., colliding/ non-colliding RS offering a performance that is within 2.5dB of the single-cell performance.

PSS/SSS, C/N = 0 dB, I/N = 20 dB	Number of PSS/SSS burst combining = 1	Number of PSS/SSS burst combining = 4
Cell ID detection probability	0.67	0.97

Table 1. *PSS/SSS performance with PSS/SSS interference cancellation.*

PBCH	Single cell	Non-interference cancellation, I/N = 16 dB	Interference cancellation, I/N = 16 dB
C/N for BLER = 1%	–9.0 dB	5.5 dB	–3.0 dB

Table 2. *PBCH performance for space frequency block coding (SFBC).*

PCFICH, C/N at SER = 1%	Single cell	Non-interference cancellation, I/N = 16 dB	Interference cancellation, I/N = 16 dB
Colliding CRS	–5.5 dB	2.2 dB	–3.3 dB
Non-Colliding CRS	–5.5 dB	8.0 dB	–2.8 dB

Table 3. *PCFICH performance.*

ference cancellation for the considered example. Single-cell PBCH performance achieves BLER = 1 percent at SNR = –9.0 dB.

Reliability of Downlink Control Channels

Downlink control channels in LTE include:
- Physical control format indicator channel (PCFICH), utilized to indicate time-domain control span: transmitted in first OFDM symbol of each subframe
- PHICH for downlink acknowledgments in response to uplink HARQ data packets: transmitted in either first OFDM symbol of each subframe or the maximum control span of that subframe depending on the PBCH parameter for PHICH duration and/or whether the subframe is MBSFN subframe or not
- Physical downlink control channel (PDCCH) for downlink control information (DCI) transmission: interleaved in time and frequency over the entire control region

PCFICH Reliability — PCFICH is transmitted in four resource element groups (REGs), which consist of four consecutive subcarriers, and the REGs for PCFICH are distributed over the entire transmission bandwidth with mapping being a function of the cell ID. PCFICH reception in scenarios with CRE or in the presence of CSG HeNBs may experience possibly high interference from the neighboring cells' CRS. Interference from CRS occurs even for the interference-free tunnel created by the ABS configuration of the dominant interferer since CRS of the neighboring cells also needs to be transmitted on those subframes. The good news is that the interference incurred from CRS can easily be removed (i.e., cancelled at the UE). Table 3 shows PCFICH link performance for a 10 MHz 2 × 2 system in the presence of a strong interferer 16 dB above thermal noise (i.e., I/N = 16 dB). ETU30 is assumed for the serving cell, and EVA30 [11] is assumed for the interfering cell.

The interfering cell is assumed to use ABS and therefore only causes interference from its CRS transmission. Simulation results are summarized in terms of required serving cell C/N and the symbol error rate (SER) of 1 percent for the colliding CRS and the non-colliding CRS between the serving cell and the interfering cell. A realistic channel estimation algorithm is assumed.

From the presented results we observe large performance degradation of PCFICH reliability without interference cancellation, particularly for the non-colliding CRS case (> 10 dB at SER = 1 percent). PCFICH performance for the interference cancellation receiver would be robust against network planning; that is, colliding/non-colliding CRS offers performance that is within 2.5 dB of the single-cell performance.

PHICH Reliability — PHICH is transmitted over three REGs in either one OFDM symbol or as many OFDM symbols as the maximum control span of that subframe (three in the case of systems with system bandwidth of 3 MHz or larger). In either case, the RE mapping is pseudo-random dependent on the PCI. Similar to the PCFICH, PHICH can experience possibly high interference from CRS of neighboring cells, which can be cancelled by the UE receiver. Table 4 shows PHICH link performance. Note that in addition to an interference cancellation receiver, we also show the performance of a receiver that performs nulling of REs, which are known to have high interference at the receiver — in this case, high-interference PHICH REs are the ones corresponding to the first OFDM symbol.

From the results we observe large performance degradation of PHICH reliability without interference cancellation or nulling, especially for the non-colliding CRS case with PHICH

PHICH, C/N at SER = 1%	Single cell	Non-interference cancellation, I/N = 16 dB	Interference cancellation, I/N = 16 dB	RE nulling, I/N = 16 dB
Colliding CRS, 1 OFDM symbols	–6.6 dB	2.0 dB	–4.4 dB	N/A
Non-Colliding CRS, 1 OFDM symbols	–6.6 dB	7.0 dB	–4.6 dB	N/A
Colliding CRS, 3 OFDM symbols	–6.4 dB	2.1 dB	–4.4 dB	N/A
Non-Colliding CRS, 3 OFDM symbols	–6.4 dB	–1.0 dB	–5.0 dB	–4.6 dB

Table 4. *PHICH performance.*

PDCCH, C/N at BLER = 1%	Single cell	Non-interference cancellation, I/N = 16 dB	Interference cancellation, I/N = 16 dB	RE nulling, I/N = 16 dB
Colliding CRS, 1 OFDM symbols	–3.5 dB	3.0 dB	–1.9 dB	N/A
Non-Colliding CRS, 1 OFDM symbols	–3.5 dB	N/A	–1.5 dB	N/A
Colliding CRS, 3 OFDM symbols	–3.5 dB	3.3 dB	–1.8 dB	N/A
Non-Colliding CRS, 3 OFDM symbols	–3.5 dB	1.3 dB	–2.4 dB	–2.1 dB

Table 5. *PDCCH performance.*

duration of one OFDM symbol. Increasing PHICH duration does not help for the case of colliding CRS due to the large degradation of channel estimation for this case. Increasing the PHICH duration to three OFDM symbols helps for the non-colliding CRS case, especially when nulling PHICH REs fall in the first OFDM symbol, which is the symbol experiencing the large interference. For this case the performance matches that of CRS interference cancellation at the expense of a downlink control overhead of 21 percent. Note that the nulling approach is not efficient for PHICH duration of one OFDM symbols since all three REGs of the PHICH are in the first OFDM symbol for that case, and all of them suffer from RS interference.

Similar to the PCFICH, PHICH performance for the interference cancellation receiver would be robust against network planning; that is, colliding/non-colliding CRS offering performance within 2.5 dB of the single-cell performance. In addition, when interference suppression is used there is no need to resort to the long PHICH duration, which increases the corresponding additional downlink overhead up to 15 percent.

PDCCH Reliability — The PDCCH is transmitted utilizing aggregation of {1, 2, 4, 8} control channel elements (CCEs) comprising 9 REGs, pseudo-randomly distributed over the entire control span in time and frequency. The reliability of the PDCCH is degraded by CRS interference from the neighboring (dominant interferer) cells.

Table 5 shows PDCCH link performance for the same assumptions as for the PCFICH and PHICH characterizations. DCI Format 1A is assumed with 43-bit payload size and four CCEs.

Results are shown for control spans of one and three OFDM symbols. Note that in addition to an interference cancellation receiver, we also show the performance of a receiver that performs nulling of REs known to have high interference at the receiver — in this case, high interference PDCCH REs are the ones corresponding to the first OFDM symbol.

From these results we also see large performance degradation of PDCCH reliability. In the non-colliding CRS case with one OFDM symbol control span, a high error rate floor is observed. Indeed, as for PHICH characterizations, increasing the control span does not help for the case of colliding CRS due to the large channel estimation degradation. Increasing the OFDM span to three OFDM symbols helps in the non-colliding CRS case especially when nulling PHICH REs correspond to the first OFDM symbol, which is the symbol experiencing the large interference. For this case the performance matches that of CRS interference cancellation at the expense of a downlink control overhead of 21 percent. As for the case of PHICH detection, the nulling approach is not efficient for a control span of one OFDM symbol since for this case all PDCCH REGs are in the first OFDM symbol and therefore suffer interference from CRS.

Similar to PCFICH and PHICH, PDCCH performance with an interference cancellation receiver would be robust against network planning, that is, colliding/non-colliding CRS offering performance within 2.5 dB of the single-cell performance. In addition, when interference suppression is used, there is no need to resort to overprovisioned control span and its corresponding additional downlink control overhead, which could be up to 15 percent.

RELIABILITY OF THE DOWNLINK DATA CHANNEL

Reliability of th e data channel is degraded from the interference created by the CRS of the neighboring (dominant interferer) cells.

Interference from CRS can be mitigated by configuration of MBSFN subframes, which do not

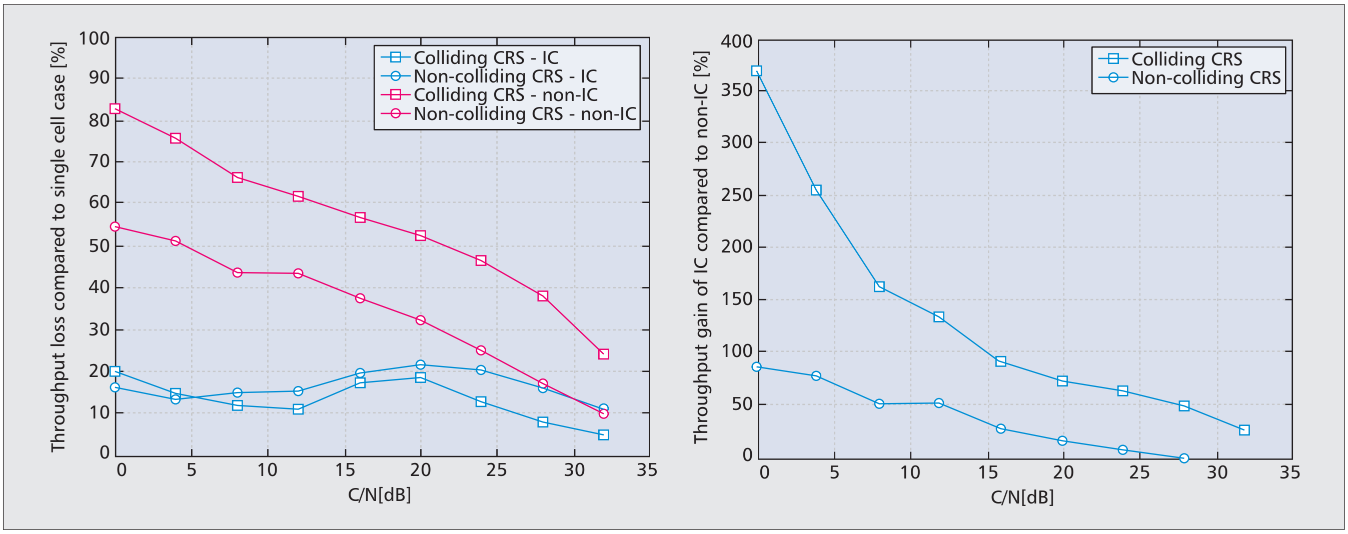

Figure 8. *PDSCH performance (SFBC). Left: Percentage throughput loss compared to single cell case. Right: Percentage throughput gain of interference cancellation (IC).*

contain CRS in the data region (i.e., OFDM symbols on which the downlink data channel is conveyed). The configuration of MBSFN subframes has an advantage in that CRS interference is completely removed. However, configuration of MBSFN subframes is relatively static in nature and hence cannot easily adapt to the varying channel traffic load. In addition, certain subframes cannot be configured as MBSFN, which has an implication on scheduling of uplink data traffic and the uplink HARQ timeline. Removal of CRS interference at the UE is an alternative that is not dependent on the configuration of MBSFN subframes and is beneficial, especially when non-MBSFN ABS should be used.

Figure 8 shows PDSCH link throughput performance for the same assumptions as for the PCFICH, PHICH, and PDCCH characterizations, with the difference that ETU3 is assumed for the serving cell and EVA3 for the interfering cell. Cascaded errors are not considered; that is, errors from the control channel are not modeled. The link throughputs are obtained by running adaptive modulation and coding, targeting 10 percent BLER after the first transmission. The transmission bandwidth is six resource blocks (RBs) randomly selected.

From the results above, we observe that CRS interference cancellation offers robust performance in the presence of strong interferers. The performance advantage is significant across a range of C/Ns, particularly in the region of interest (I/N is greater than C/N). Note that LTE Rel-10 effectively only allows for CRS cancellation for non-colliding CRS cases, as UE is not aware of the PCIs that can be cancelled in case of CRS collisions, and for that reason cannot perform appropriate RLM procedure and report accurate CSI feedback.

System Performance

The benefits of CRE and an interference cancellation receiver can be demonstrated for macro-pico and macro-CSG HeNB scenarios. In both cases, system performance can be improved if the users are not associated with the strongest downlink cell.

Macro-Pico Scenario

Consider four picocells randomly placed in the coverage of a macrocell and uniform distribution of usersin the system simulation methodology [11] referred to as Config1. The traffic model commonly used to evaluate system performance models data arrival as a random Poisson process, where file size is the same across users [11]. For the purpose of this analysis, we consider a file size of 2 Mbytes.

We evaluate of benefits of CRE with cell biasing and interference cancellation by comparing biasing of 10 and 18 dB toward picocells for the resource partitioning case with CRE, and 0 dB biasing when resource partitioning is not utilized. The simulation assumptions are aligned with [11], where Channel Model 1 is selected to model path loss between eNB and UE, and a proportional fair scheduler is used.

The trade-off between the cell edge and total cell throughput results are illustrated in Fig. 9. It should be first noted that the comparison is to a certain extent complicated by the fact that for the same scheduling algorithm, the resulting fairness is different for different deployment scenarios. Nevertheless, we clearly observe that compared to the case without CRE, limited cell throughput gains are achieved if cell biasing is combined with a receiver that does not suppress CRS interference in ABS. The reason for the limited gain is that significant CRS interference is experienced by pico UE on the data tones in which the macrocell transmits CRS. Significantly higher gains are achieved with receivers that explicitly suppress interference from CRS. For cell biasing of 6 dB and CRS interference cancellation, the cell throughput gain is about 17 percent for equal cell edge throughput values; hence, the gain is larger when the comparison is made accounting for equal cell edge throughput values. Note that the overall gains are larger when cell biasing of 12 to

18 dB is utilized, and vary between 28 and 56 percent, depending on the bias value and reference point used for comparison.

Macro-CSG HeNB Scenario

The benefits of the time domain eICIC and interference cancellation at the UE can also be observed for co-channel deployments of CSG HeNBs in a macro network. The main issue with CSG HeNBs is the ability of the UE to detect a macro eNB when in coverage of a non-member CSG HeNB. To show the benefit, we evaluate the performance for the HeNB deployment model described in [1], referred to as dual-strip mode, illustrated in Fig. 10. We also consider an autonomous open loop power control algorithm used to minimize interference to the macro network. The power control algorithm adjusts the power of HeNB to provide macro UE coverage for path loss values of up to 60 dB. Table 6 shows the outage values as a function of cell acquisition capability of the macro UE and illustrates the potential outage reduction obtained by interference-cancellation-capable UE receivers.

Time domain eICIC among HeNBs and a macro network coupled with power control at HeNBs and interference-cancellation-capable UE receivers enables reliable operation at low geometries, which can virtually eliminate service outage for macro UE.

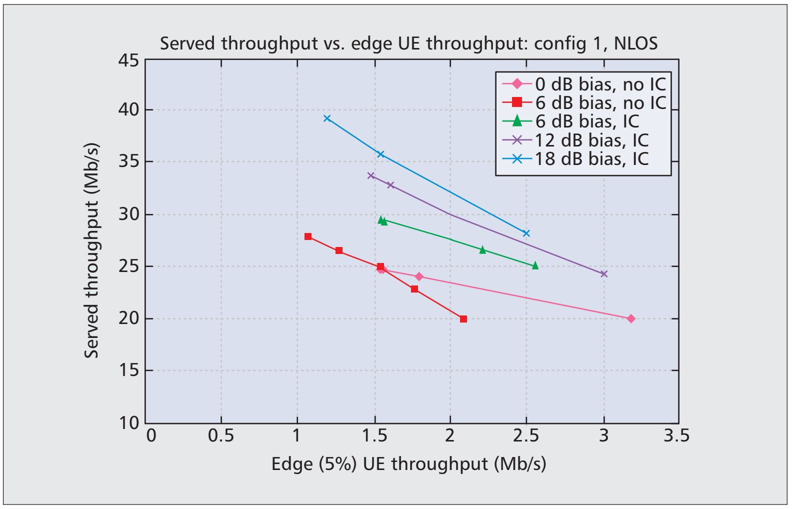

Figure 9. *Served cell throughput as a function of cell edge performance with and without CRE and interference cancellation at UE.*

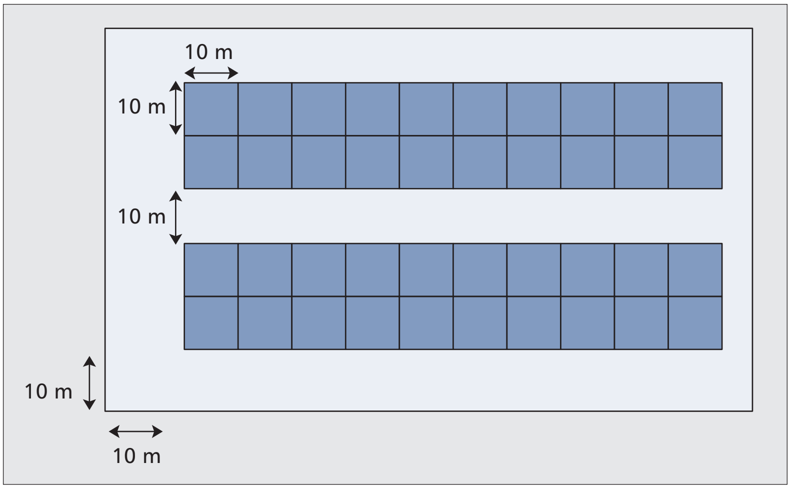

Figure 10. *Dual-strip model.*

Outage threshold for acquisitions channels	Dual-strip (35% indoor macro UEs)	Dual-strip (80% indoor macro UEs)
–8 dB	13%	28%
–18 dB	7%	12%
–28 dB	3%	4%

Table 6. *System outage percentage as a function of UE cell acquisition capability for dual strip model.*

Future Trends

It has been shown that interference cancellation can provide significant performance advantage over a conventional receiver that treats CRS and PSS/SSS/PBCH interference as white noise. The large link performance gain translates into the system throughput gain illustrated earlier.

The system simulation results shown earlier assume network planning, where macro- and picocells utilize PCIs that correspond to different CRS resource element shifts, avoiding the CRS "collision" between the macro- and picocells. However, such a planning mechanism may not always be feasible, and when that is the case, CRS "collision" would occur. LTE Rel-10 does not provide for a mechanism to address "colliding" CRS other than relying on the configuration of MBSFN subframes, which eliminates the interference in the data region, but CRS interference in the control region remains. Addressing the "colliding" CRS case is one of priorities of the Rel-11 work. The other is benchmarking the interference cancellation receiver performance. Benchmarking the performance is necessary in order for the network to fully exploit interference cancellation capability at the UE in heterogeneous networks. The network needs to know the receiver capability in order to properly balance the load and perform handovers between macro and pico/CSG HeNB cells.

The Rel-10 eICIC mechanism allows for both time and frequency partitioning of resources in order to reduce interference. Possible extension to the spatial domain is being studied in Rel-11. Coordination of utilized beams between neighboring eNBs is considered as a possible approach to reduce intercell interference that would mainly benefit users at the cell edge.

Conclusions

Deployment of heterogeneous networks, with new and improved eICIC mechanism coupled with UE ability to suppress interference due to reference (pilot) signals and acquisition signals and channels from strong interferers, enable substantial gains in overall system capacity.

Heterogeneous networks allow for a flexible deployment strategy where eNBs with different power are used to provide coverage and capacity where it is needed the most. The eICIC mecha-

Deployment of heterogeneous networks, with the new and improved eICIC mechanism coupled with UE ability to suppress interference due to reference (pilot) signals and acquisition signals and channels from strong interferers, enable substantial gains in overall system capacity.

nism maximizes bits per seconds per hertz per unit area by controlling inter-eNB throughput and enabling a more uniform user experience.

Interference cancellation capability at the UE removes interference from reference signals and acquisition signals and channels that are utilized for cell acquisition and connection management. Without suppression of the interference from these signals and channels, the system gains due to eICIC would all be virtually lost. Benchmarking the UE performance is necessary in order for the network to fully exploit the advantages that deployment of heterogeneous networks and eICIC can offer.

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REFERENCES

[1] 3GPP TS36.300 V8.9.0 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 8).

[2] 3GPP TS 36.300 V10.3.0 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 10).

[3] M. Yavuz *et al.*, "Interference Management and Performance Analysis of UMTS/HSPA+ Femtocells," *IEEE Commun. Mag.*, 2009.

[4] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell Networks: A Survey," *IEEE Commun. Mag.*, 2008.

[5] M. Vajapeyam *et al.*, "Downlink FTP Performance of Heterogeneous Networks for LTE-Advanced," *IEEE ICCC*, Kyoto, Japan, 2011.

[6] Y. Peng and F. Qin, "Exploring Het-Net in LTE-Advanced System — Interference Mitigation and Performance Improvement in Macro-Pico Scenario," *IEEE ICCC*, Kyoto, Japan, 2011.

[7] S. Yeh *et al.*, "Power Control Based Interference Mitigation in Multi-Tier Network," *IEEE GLOBECOM Wksp.*, 2010.

[8] A. Barbieri *et al.*, "LTE Femtocells: System Design and Performance Analysis," *IEEE VTC '11*.

[9] 3GPP TS36.423 V10.1.0 Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 application protocol (X2AP); (Release 10).

[10] 3GPP TR36.921 V2.0.0 Evolved Universal Terrestrial Radio Access (E-UTRA); FDD Home eNodeB (HeNB) Radio Frequency (RF) requirements analysis (Release 9).

[11] 3GPP TR 36.814, "E-UTRA; Further Advancements for E-UTRA Physical Layer Aspects."

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