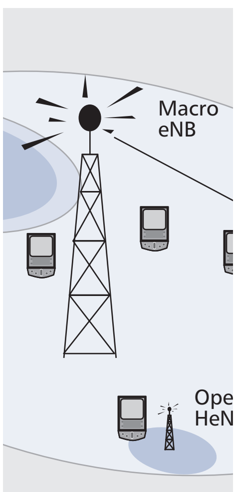
A SURVEY ON 3GPP HETEROGENEOUS NETWORKS

ALEKSANDAR DAMNJANOVIC, JUAN MONTOJO, YONGBIN WEI, TINGFANG JI, TAO LUO, MADHAVAN VAJAPEYAM, TAESANG YOO, OSOK SONG, AND DURGA MALLADI, QUALCOMM INC.



As the spectral efficiency of a point-to-point link in cellular networks approaches its theoretical limits, with the forecasted explosion of data traffic, there is a need for an increase in the node density to further improve network capacity.

ABSTRACT

As the spectral efficiency of a point-to-point link in cellular networks approaches its theoretical limits, with the forecasted explosion of data traffic, there is a need for an increase in the node density to further improve network capacity. However, in already dense deployments in today's networks, cell splitting gains can be severely limited by high inter-cell interference. Moreover, high capital expenditure cost associated with high power macro nodes further limits viability of such an approach. This article discusses the need for an alternative strategy, where low power nodes are overlaid within a macro network, creating what is referred to as a heterogeneous network. We survey current state of the art in heterogeneous deployments and focus on 3GPP LTE air interface to describe future trends. A high-level overview of the 3GPP LTE air interface, network nodes, and spectrum allocation options is provided, along with the enabling mechanisms for heterogeneous deployments. Interference management techniques that are critical for LTE heterogeneous deployments are discussed in greater detail. Cell range expansion, enabled through cell biasing and adaptive resource partitioning, is seen as an effective method to balance the load among the nodes in the network and improve overall trunking efficiency. An interference cancellation receiver plays a crucial role in ensuring acquisition of weak cells and reliability of control and data reception in the presence of legacy signals.

INTRODUCTION

Data traffic demand in cellular networks today is increasing at an exponential rate. As the link efficiency is approaching its fundamental limits, further improvements in system spectral efficiency are only possible by increasing the node deployment density. In a relatively sparse deployment of macro base stations, adding another base station does not severely increase intercell interference, and solid cell splitting gains are easy to achieve. However, in already dense deployments today, cell splitting gains are significantly reduced due to already severe intercell interference. Moreover, site acquisition costs in a capacity limited dense urban area can get prohibitively expensive.

Challenges associated with the deployment of traditional macro base stations can be overcome by the utilization of base stations with lower transmit power. As we will further discuss below, we classify low power nodes as pico, femto and relay nodes. If the low power nodes are intended for outdoor deployments, their transmit power ranges from 250 mW to approximately 2 W. They do not require an air conditioning unit for the power amplifier, and are much lower in cost than traditional macro base stations, which transmit power typically varies between 5 and 40 W. Femto base stations are meant for indoor use, and their transmit power is typically 100 mW or less. Unlike pico, femto base stations may be configured with a restricted association, allowing access only to its closed subscriber group (CSG) members. Such femto base stations are commonly referred to as closed femtos. A network that consists of a mix of macrocells and low-power nodes, where some may be configured with restricted access and some may lack wired backhaul, is referred to as a *heterogeneous network* and is illustrated in Fig. 1.

Femto cells have recently attracted significant attention. There are a number of technical studies associated with various aspects of femto cells deployments based on cellular technology such as third-generation (3G) High Speed Packet Access (HSPA) or 1xEV-DO. These studies consider operations, administration, and management (OAM) and self organizing network (SON) protocols, network architecture, local IP access (LIPA), access (open, closed, and hybrid), and interference management [1–3, references therein]. In addition, heterogeneous networks based on different access technologies, where macro network is based on a cellular technology and low power access points are based on WLAN have also been studied in literature [4, 5]. Reduced cost is one of the main drivers for the adoption of femto cells. It was shown in [6] that in urban areas a combination of publicly accessible home base stations or femto cells (randomly deployed by the end

 1536-1284/11/$25.00 © 2011 IEEE

user), and macrocells deployed by an operator for area coverage in a planned manner, can result in significant reductions (up to 70 percent in the investigated scenario) of the total annual network costs compared to a pure macro-cellular network deployment. If a wired backhaul is not available, relay nodes can be deployed where the air interface spectrum is used for backhaul connectivity and to provide access to terminals [7]. In this case, the relay node appears as user equipment (UE) to the macro base station and as a regular base station to the UE it serves.

Straightforward co-channel deployment of low-power nodes has its own challenges. The introduction of low-power nodes in a macro network creates imbalance between uplink and downlink coverage. Due to larger transmit power of the macro base station, the handover boundary is shifted closer to the low-power node, which can lead to severe uplink interference problems as UE units served by macro base stations create strong interference to the low-power nodes. Given the relatively small footprint of low-power nodes, even in the case of the most optimized placement, low-power nodes may become underutilized due to geographic changes in data traffic demand. The performance of a mixed deployment of macro, pico, and open femto cells was evaluated in [8, 9], which showed that the limited coverage of low-power nodes is the main reason for limited performance gain in heterogeneous networks.

Furthermore, some of the deployed femto cells may have enforced restricted association, which effectively creates a coverage hole and exacerbates the interference problem. In order to cope with the interference, it is necessary to introduce techniques that can adequately address these issues. A well-known baseline interference management and self-configuration solution for 3G femtocells (i.e., HSPA or 1xEVDO femtocells) is downlink transmitter power control. As mentioned above, due to restricted association, a closed femtocell creates a downlink coverage hole at the vicinity of the femtocell for non-member UE [8]. In order to reduce the coverage hole, a femtocell could adapt the transmitted power intelligently such that interference is not leaked outside the intended coverage area such as a residential home. This technique is often assisted by a network listening module (NLM), where a femtocell monitors macrocell signal strength occasionally on the same channel. Since the femto coverage and femto interference to the macro UE are directly proportional to the femto to macro signal strength ratio, a femtocell could set the proper transmit power by estimating the additional interference that could be tolerated by non-member UE near the femtocell. As a result, the femtocell maintains a similar coverage area regardless of its location within the embedded macrocell. The network capacity of heterogeneous networks with mixed macro- and closed femtocell deployments were investigated in [10–12], and significant gain was shown when dynamic femtocell transmit power control was utilized.

Further enhancement to this technique is UE-enhanced femtocell transmit power setting.

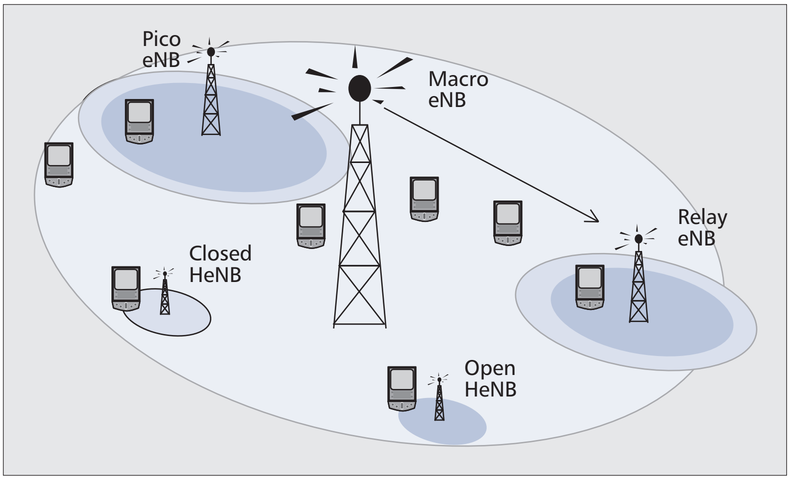


Figure 1. *Heterogeneous network topology utilizing a mix of high-power (macro) and low-power base stations.*

For example, when non-member UE attempts to access a femtocell, the femtocell rejects the attempt due to restricted access. At the same time, the femtocell could also obtain information about the macro UE during the access handshake. By intelligently processing the femto UE and macro UE information, a proper femtocell transmitter power could be chosen.

On the uplink, femto UE and macro UE could create high interference, which can lead to high interference variation. Due to the downlink power mismatch, UE that receives similar signal strength from the macro- and femtocells is much closer to the femtocell than the macrocell. In the case of nominal transmit power of the macro base station at 43 dBm and femto at 20 dBm, the received power difference on uplink would be as high as 23 dB (i.e., the received power at the femtocell is 23 dB higher than the received power at the macrocell). If this UE is served by the macrocell with a targeted received signal-to-noise ratio of 5 dB, the interference caused by this UE would be 28 dB above the thermal at the femtocell when this UE starts transmitting. In order to cope with such large interference variation, in 3G systems a femtocell could use adaptive noise padding at the receiver to damp down the total interference plus noise level variation [13].

In 3G networks, pico deployments are also popular for hotspot coverage. Maximum gain is achieved by adjusting the handover boundary between the macro- and picocells. For example, when a macro experiences a high load, it could hand over UE to a picocell early. However, due to co-channel interference, adjustment of handover boundary is quite limited,; handover to a very weak cell could cause radio link failure.

Given the interference scenarios deployment of low-power nodes can create, it is clear that an introduction of a mechanism that allows flexible association between a serving base station and a UE, and that mitigates downlink and uplink interference would be beneficial. In 4G networks, new physical layer design allows for flexible time and frequency resource partitioning. This added flexibility enables macro- and femto/picocells to assign different time-frequen-

Compared to 3G technologies, such as 3GPP's HSPA, LTE Rel-8 offers higher peak data rates due to larger system bandwidth (up to 20 MHz was allowed) and higher-order MIMO spatial processing techniques.

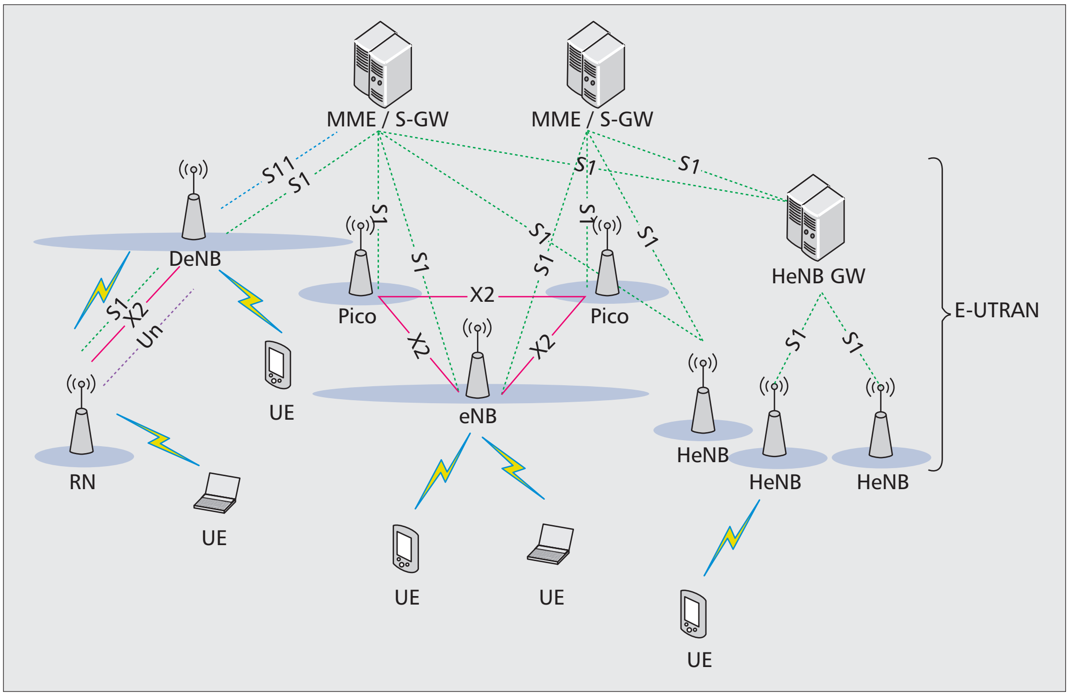


Figure 2. *LTE heterogeneous network nodes and their interfaces.*

cy resource blocks within a carrier or different carriers (if available) to their respective UE. This is one of the intercell interference coordination (ICIC) techniques that can be used on the downlink to mitigate data interference [14, 15]. With additional complexity, joint processing of serving and interfering base station signals could further improve the performance of heterogeneous networks [16, 17], but these techniques require further study for the scenarios commonly seen in practice.

For those reasons, in the context of Long Term Evolution (LTE) standardization, the Third Generation Partnership Project (3GPP) is discussing the concept of cell range expansion through handover biasing and resource partitioning among different node power classes. The biasing mechanism allows for load balancing, where depending on the bias value, the network can control the number of UE units associated with the low-power nodes and therefore control traffic demand at those nodes. Resource partitioning, which can also be adaptive, allows configuration and adjustment of interference protected resources, enabling UE in a cell expanded area to receive data. Moreover, the same resource partitioning technique provides a mechanism to mitigate uplink interference and allows non-CSG member UE to receive service when in proximity of closed femtocells.

The main goal of this article is to provide an overview of the topology and the deployment options for heterogeneous networks. We focus on LTE downlink, where we review the current state of the art, describe technical challenges, and give some thoughts on future research directions. Uplink data transmissions are slaved to the downlink control channel, and interference management techniques enabled to partition downlink resources apply to the uplink transmissions too.

LTE Overview

The first release of LTE was published in March 2009 and is referred to as LTE Rel-8 [18]. 3GPP has developed the LTE standard for fourth-generation (4G) cellular networks based on orthogonal frequency-division multiplexing (OFDM) waveform for downlink (DL) and single-carrier FDM (SC-FDM) waveform for uplink (UL) communications mainly to improve the user experience for broadband data communications. Compared to 3G technologies, such as 3GPP's HSPA,[1] LTE Rel-8 offers higher peak data rates due to larger system bandwidth (up to 20 MHz was allowed) and higher-order multiple-input multiple-output (MIMO) spatial processing techniques (up to 4 Tx × 4 Rx open and closed loop MIMO schemes are supported in the DL of LTE Rel-8).

Figure 2 illustrates the LTE network [18] nodes and the interfaces among them. The base stations are denoted eNode-B (eNB) and the mobile stations or terminals as UE. The low-power nodes include picocells, femtocells, home eNBs (HeNBs), and relay nodes (RNs). The eNB serving the RN (i.e., scheduling RN backhaul traffic) is denoted donor eNB (DeNB). The same eNB can be the DeNB for one RN and the regular serving cell for UE, as shown in Fig. 2. The mobility management entity (MME) and serving gateway (S-GW) serve as local mobility anchor points for the control and data planes, respectively.

The X2 interface defined as a direct eNB-to-eNB interface allows for inter-cell interference coordination (ICIC). The Rel-8 ICIC techniques can be summarized as:

- *Proactive*: Techniques that facilitate fractional frequency reuse (FFR) or "soft reuse" operation in the DL and UL with the goal of reducing interference experienced in certain

[1] HSPA Rel-10 supports carrier aggregation mode, where four 5 MHz can be aggregated offering broadband wireless communication to a single UE over 20 MHz bandwidth.

frequency subbands in order to increase the cell edge user throughput

- *Reactive*: Techniques that respond to high-interference conditions and enable tight control of the interference-over-thermal (IoT) level in the UL

These ICIC techniques are expanded in Rel-10 to enable efficient support of co-channel heterogeneous network deployments, discussed later. S1 and S11 interfaces support transfer or user and data traffic between the corresponding nodes and are not utilized for ICIC. The Un interface refers to an air interface between DeNB and RN. Un is based on a modified interface between the eNB and UE in order to allow half duplex operation for the RN.

As mentioned above, the LTE air interface is based on OFDM in the DL and SC-FDM in the UL. The basic time and frequency unit in the DL (UL) is one OFDM (SC-FDM) symbol and one subcarrier (virtual subcarrier), respectively. The subcarrier spacing is 15 kHz and therefore, the OFDM symbol duration is 66.67 us. Each OFDM/SC-FDM symbol is pre-appended with a cyclic prefix (CP) to suppress the inter-symbol interference and mitigate multi-path. Two CP durations are defined; the normal CP has a duration of 4.7 us and the extended CP has a duration of 16 us. One resource element corresponds to one subcarrier (virtual subcarrier) in one OFDM (SC-FDM) symbol. OFDM (SC-FDM) symbols are grouped in subframes of 1 ms duration. Each subframe is composed of two 0.5 ms slots. In order to limit the signaling overhead of data allocations, the minimum scheduling unit for the DL and UL of LTE is referred to as a resource block (RB). One RB pair consists of 12 subcarriers in the frequency domain (i.e., 180 kHz) and one subframe in the time domain (i.e., 1 ms). In the DL, all the control information is time-division multiplexed (TDM) with the data transmission. The DL control information is concentrated in the first slot of the first subframe, and dynamically spans the first one, two, or three OFDM symbols of the subframe.

Subframes are further grouped in 10 ms radio frames. Figure 3 illustrates the physical layer frame structure for FDD. Each radio frame has two 5 ms halves containing the signals necessary to obtain the physical identity of the cell. These signals are what we call the *acquisition channels*, which are the primary and secondary synchronization signals, providing the physical cell identity (PCI) of the cell, and the physical broadcast channel (PBCH), which provides some critical system information such as the DL transmission bandwidth and the number of DL antenna ports. The acquisition channels share the property of spanning the middle six RBs of the system bandwidth. This enables having the same acquisition channels irrespective of the actual system bandwidth (up to 20 MHz is supported for Rel-8).

LTE defines a reference or pilot signal in Rel-8, referred to as a common reference signal (CRS), which is used for mobility measurements as well as for demodulation of the DL control and data channels. The CRS transmission is distributed in time and frequency, as shown in Fig. 3, to enable adequate time and frequency interpolation of the channel estimates for the purpose of coherent reception of the transmitted signals in time- and frequency-selective channels.

As discussed later, co-channel deployments of heterogeneous networks rely on the coordination of *almost blank subframes*. Almost blank subframes are intended to reduce the interference created by the transmitting node while providing full legacy support. For that reason, on almost blank subframes, eNB does not schedule unicast traffic while transmitting acquisition channels and CRS to provide legacy support.

3GPP has been working on further improving the spectral efficiency of LTE as part of its Rel-10 version. LTE Rel-10 is being developed to meet ITU requirements for IMT-Advanced technology. LTE Rel-10 [19], also termed LTE-Advanced (LTE-A), supports improved MIMO operation as DL MIMO support is enhanced (8 Tx × 8 Rx is supported), and UL MIMO (4 Tx × 4 Rx) is introduced to improve link spectral efficiency. Signaling mechanisms enabling aggregation of multiple carriers are also introduced in LTE Rel-10, offering improvements in peak user data throughput. Up to five 20-MHz component carriers can be aggregated, offering a peak data rate of more than 1 Gb/s. However, these improvements, while significant from the link perspective and for users in good coverage, or in terms of the peak data rates for lightly loaded systems, do not translate into significant improvements in terms of system spectral efficiency in bits per second per Hertz. System gains are only achievable through increased node density and deployment of low-power nodes, such as pico, femto, and relay base stations.

PICOCELLS

Picocells are regular eNBs with the only difference of having lower transmit power than traditional macro cells. They are, typically, equipped with omni-directional antennas, i.e., not sectorized, and are deployed indoors or outdoors often in a planned (hot-spot) manner.

Their transmit power ranges from 250 mW to approximately 2 W for outdoor deployments, while it is typically 100 mW or less for indoor deployments. Since picocells are regular eNBs from the architecture perspective, as can be seen in Fig. 2, they can benefit from X2-based intercell interference coordination (ICIC).

FEMTOCELLS

Femtocells or HeNBs are typically consumer deployed (unplanned) network nodes for indoor application with a network backhaul facilitated by the consumer's home digital subscriber line (DSL) or cable modem. Femtocells are typically equipped with omnidirectional antennas, and their transmit power is 100 mW or less.

Depending on whether the femto cells allow access and hence usage of the consumer's home DSL or cable modem to all terminals, or to a restricted set of terminals only, femto cells are classified as open or closed. Closed femtos restrict the access to a closed subscriber group (CSG), while open femtos are similar to picocells but with the network backhaul provided by the home DSL or cable modem. A femtocell can also be hybrid, whereby all terminals can access

Picocells are regular eNBs, with the only difference of having lower transmit power than traditional macrocells. They are, typically, equipped with omnidirectional antennas (i.e., not sectorized) and are deployed indoors or outdoors, often in a planned (hotspot) manner.

but with lower priority for the terminals that do not belong to the femto's subscriber group.

Since closed femtos do not allow access to all terminals, they become a source of interference to those terminals. Co-channel deployments of closed femtos therefore cause coverage holes and hence outage of a size proportional to the transmit power of the femtocell.

Figure 2 shows the architecture of LTE femtocells (HeNBs), and, as can be seen, no X2 interface is defined for HeNBs in Rel-8/9. The absence of an X2 interface for closed femtos does not make ICIC possible for this type of node. Instead, OAM-based techniques in conjunction with possibly autonomous power control techniques are the only viable interference control techniques for Rel-10. These techniques seek to minimize the outage these network nodes cause around them by enabling reception of the signal from the closest macrocell in close proximity to the closed femto.

Relay Node

An RN is a network node without a wired backhaul. The backhaul, which provides the attachment of the RN to the rest of the network, is

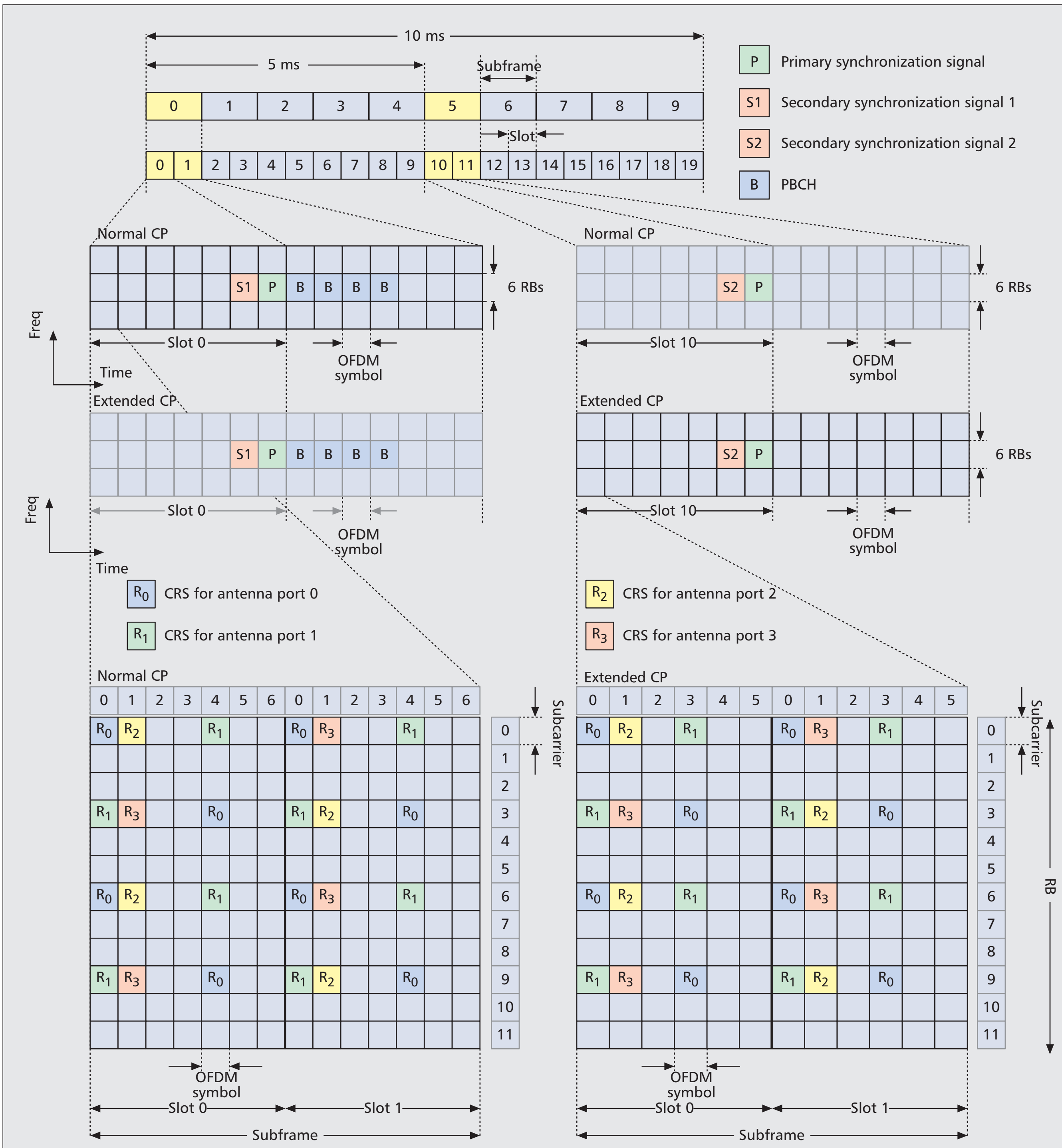


Figure 3. *LTE DL physical layer structure for FDD.*

wireless and uses the air interface resources of the wireless system in question. In case the backhaul communication takes place in the same frequency as the communication to/from UE on DL/UL, respectively, the relays are denoted as in-band. If the backhaul communication takes place at a frequency different to that used by UE in DL and UL, the relay node is classified as out-of-band. Note that unlike in-band relays, out-of-band relays do not pose many physical layer design challenges. However, out-of-band relays require additional dedicated spectrum for backhaul operation and therefore are far less attractive than their in-band counterparts. As a result, in-band relaying has been the focus of study in 3GPP.

The *backhaul link* denotes the DeNB to relay link; the *access link* denotes the RN to UE link; and the *direct link* denotes the eNB to UE link (without relay participation). An RN can be half-duplex (HD) or full-duplex (FD). This categorization is relevant for in-band relays where for the DL, the eNB-to-relay transmission takes place in the same frequency as the relay-to-UE transmission (i.e., backhaul and access links are at the same frequency). Similarly, for the UL, the UE-to-relay transmission takes place in the same frequency as the relay-to-eNB transmission. HD operation is motivated to avoid desensing the RN receiver if it had to transmit and receive at the same frequency and at the same time. Therefore, HD relays will, at a given time, either transmit to the UE on the access link or listen to its DeNB on the backhaul link for DL communications, and transmit to the eNB on the backhaul link or listen to the UE on the access link for UL communications. FD relays are able to transmit and receive at the same time on different links, relying on spatial separation between access and backhaul links (e.g., by antenna directivity or antenna location for both links) and possibly on interference cancellation capabilities of such relay nodes. Relay nodes are full-fledged eNBs without a wired backhaul. There are independent HARQ entities at the backhaul link, i.e., between the donor eNB and the relay node, and at the access link, i.e., between the relay node and the UE.

Relay nodes are typically equipped with directional antennas in the backhaul link (pointing to the DeNB) and omnidirectional antennas in the access link. RNs are deployed indoors or outdoors. Their transmit power ranges from 250 mW to approximately 2 W for outdoor deployments, while it is typically 100 mW or less for indoor deployments. Figure 2 shows the architecture of the RNs. Since there is an X2 interface to the DeNB, RNs can benefit from X2-based ICIC.

Deployment Scenarios and Technical Challenges

Heterogeneous networks are networks deployed with a mix of traditional (high-power) macro and (low-power) pico, femto, and/or relay nodes. In addition to possibly having a mix of open and closed subscriber access, this type of networks is characterized by large disparities in the transmit power used by different types of network nodes. Such power disparities, in general, put the low-power nodes (pico, femto, and relay) at a disadvantage relative to the high-power nodes (macrocells). In addition, the deployment of CSG cells poses the challenge of how to share physical resources (time/frequency) with the macrocell to avoid creating coverage holes in the macro network. Figure 4 illustrates deployment options that are further discussed below.

Multicarrier Deployment

A simple solution to avoid macro coverage being affected by the deployment of closed femtocells is, as illustrated in Fig. 4a, to deploy the closed femtocells on a carrier frequency different than that of the macro network. While this solution is effective in avoiding the interference caused by the closed femtocells, it is highly inefficient as it requires at least two carrier frequencies and creates undesirable bandwidth segmentation.

The same solution can be used for the deployment of picocells, open femtos, and RNs, where one carrier frequency is used by the high-power nodes (macrocells) and another carrier frequency is used by the low-power nodes (picocells, open femtos, and RNs). Since the transmit power characteristics of the nodes transmitting on each of the component carriers are the same, there is no power disparity and hence no interference problem: each frequency layer is homogeneous. While for the closed femto case the motivation to deploy closed femto on a carrier frequency different than that of the macro network is to avoid the creation of macro coverage outages from the deployment of closed femtos, the same cannot be said for the other (open access) low-power nodes. For this case, the macro network and the low-power nodes could both use the two carrier frequencies; and therefore, terminals that can aggregate the reception of more than one carrier could benefit from the availability of the entire available spectrum.

Carrier Aggregation

Consider the scenario where, as shown in Fig. 4b, one carrier frequency is used for macro coverage and another is shared by macrocells and closed femtocells. Interference from the closed femtocell to the macro coverage is avoided since one carrier frequency is used only by macrocells. The other carrier frequency is shared between macrocells and closed femtocells.

Carrier-aggregation-capable UE can benefit from ubiquitous coverage of the macro network in one of the carrier frequencies and partial coverage (outside of the closed femto coverage) on a second carrier frequency. At the same time, closed femtocells will continue providing coverage in their respective carrier frequency. Note that this example can be generalized to the case where more than one carrier frequency is dedicated to closed femtocells to alleviate the closed-femto-to-closed-femto interference problem arising from having a single carrier frequency for the entire closed femto deployment. Therefore, carrier aggregation enables the full use of (frequency) resources by the macro network without compromising the closed femto coverage.

While the closed femto case is a very obvious

Relay nodes are full-fledged eNBs without a wired backhaul. There are independent HARQ entities at the backhaul link (i.e., between the donor eNB and the relay node(and at the access link (i.e., between the relay node and the UE).

While the closed femto case is a very obvious example showcasing the benefits of carrier aggregation in heterogeneous networks, a similar reasoning can follow for other types of (low-power) nodes: pico cells, open femtos, and relay nodes.

example showcasing the benefits of carrier aggregation in heterogeneous networks, a similar reasoning can follow for other types of (low-power) nodes:, picocells, open femtos, and relay nodes. These types of nodes, as discussed above, are intrinsically disadvantaged with respect to high-power macrocells. It is important to note that in the case of deploying low-power nodes with open access, the coverage of the macro network is not jeopardized by the deployment of these nodes. However, targeting the regular macro coverage in one of the carrier frequencies by setting the power of the macrocells to their nominal value while deploying low-power nodes on another carrier frequency would maximize the capacity gains.

The macrocells can also transmit at the carrier frequency of the low-power nodes but with reduced power to avoid a large power disparity that would overwhelm the coverage of the low-power nodes. Conversely, the (harmless) low-power nodes can be deployed in the carrier frequency originally used by the macro network. As a result, for this example, one carrier frequency would be used by the macro network to provide nominal macro coverage (macrocell transmission at full power). The low-power nodes would also use this carrier frequency for capacity enhancement at locations close to these nodes. Another carrier frequency would be used by low-power nodes and by macrocells with reduced transmit power. In this case, clearly, carrier-aggregation-capable UE would benefit from the fact that both types of nodes use two carrier frequencies.

Therefore, carrier aggregation can be a pow-

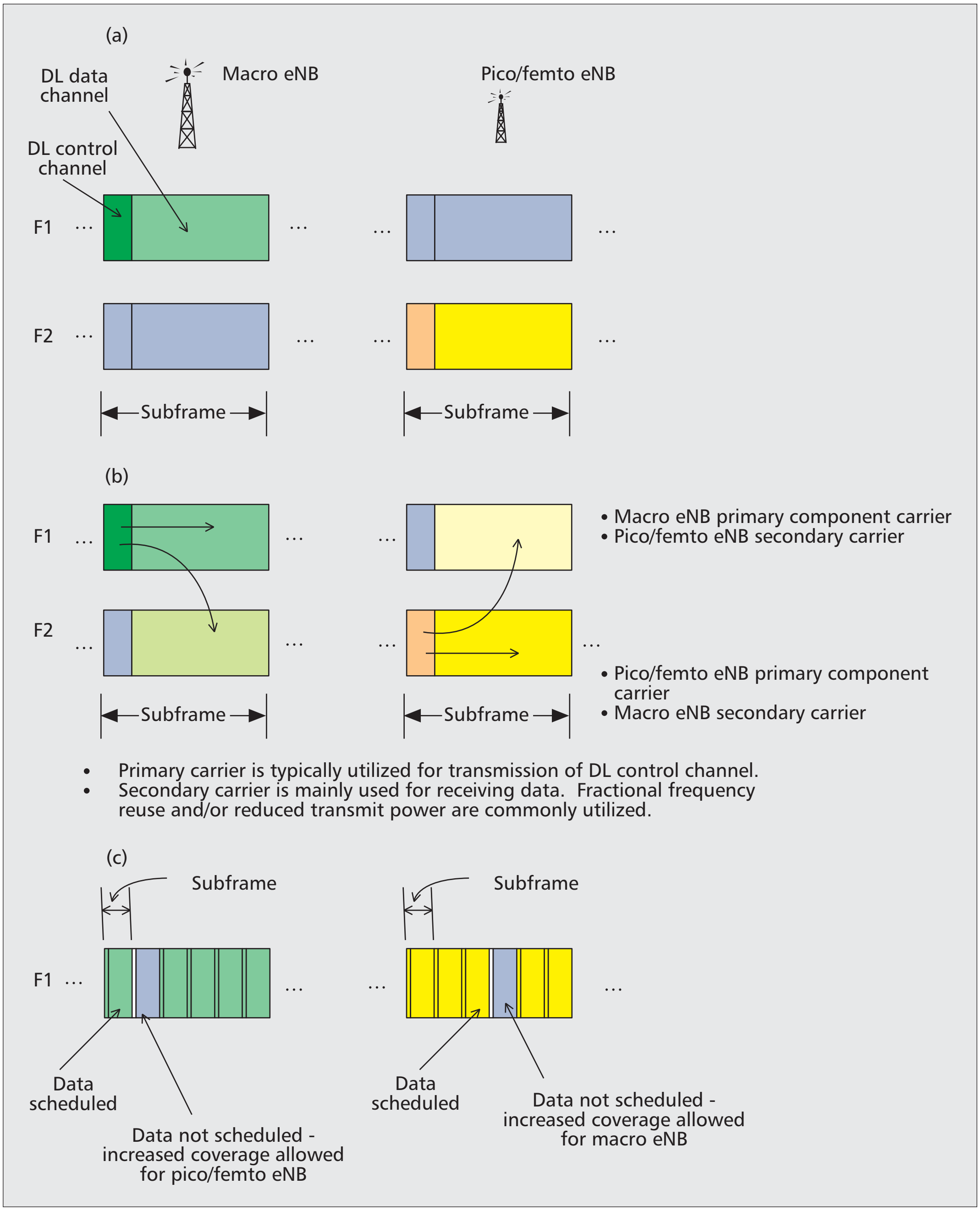


Figure 4. *Multicarrier, carrier aggregation, and co-channel deployments.*

erful tool for efficient deployment of heterogeneous networks without causing a loss of bandwidth. However, carrier-aggregation-based solutions require the availability of a good amount of spectrum and do not really scale down to small system bandwidths because of the inefficiency associated with such transmission bandwidths, including peak rate limitations for the UE that is not carrier-aggregation-capable. The cost of carrier-aggregation-capable UE and low-power nodes could become an issue as well.

Co-Channel Deployment

A third option to deploy heterogeneous networks is illustrated in Fig. 4c, and we refer to it as co-channel deployment. In this scenario, all the network nodes are deployed in the same frequency layer to avoid bandwidth segmentation, to be applicable for any system bandwidth not necessarily relying on high spectrum availability, and to avoid relying on carrier aggregation support at the terminals.

As discussed above, deploying low-power nodes at the same frequency layer as the (high-power) macrocells presents severe interference problems in the case of closed femtos. Also, for the case of open access nodes (open femtos, picocells, and RNs), the coverage of the low-power nodes is overshadowed by the transmissions of the high-power nodes; therefore, the benefits of the introduction of low -power nodes for the overall system capacity are somewhat limited.

It is therefore necessary to consider interference coordination techniques that can solve these problems. In summary, the following is desired:

- Reduction of closed femto interference to the macro layer
- Maximizing the performance benefits from the introduction of open access low-power nodes

To enable efficient support of co-channel deployment of heterogeneous networks, an interference management scheme should be able to adapt to different traffic loads and different numbers of low-power nodes at various geographical areas. In this article, we focus on co-channel deployments, and the next section goes into the details of interference management techniques that enable efficient co-channel deployment of heterogeneous networks.

Co-channel deployment of heterogeneous networks is attractive for many reasons. It is the only feasible solution when spectrum is limited (20 MHz or less), and the peak data rate performance of legacy Rel-8 UE does not need to be impacted. It is suitable for deployment of low-cost single-carrier low-power base stations, and does not require higher-cost carrier-aggregation-capable UE.

Interference Management for Co-Channel Deployments

The role of resource partitioning for interference management is critical in co-channel deployments. But, as seen below, to reach its full potential, resource partitioning needs to be paired with interference-cancellation-capable UE. Even though the focus of the article is on the DL, we should note that the same partitioning scheme applies to uplink as well since uplink data transmissions are slaved to the downlink control channel.

Pico/Relay Deployments

In this section, we focus on the case with open access low-power nodes. Throughout the text we refer to low-power nodes as pico base stations. It should be noted, however, that the same mechanism can be applied in the case of relay base stations, where the only caveat is that the X2 backhaul link between the macro and relay base stations is over the LTE air interface. Similar techniques can be applied when closed femtocells are deployed, but as discussed earlier, due to the lack of an X2 interface, only a static OAM-based solution is feasible.

Adaptive Resource Partitioning — Adaptive interference management in LTE Rel-10 is enabled through X2 backhaul coordination of resources used for scheduling data traffic. The granularity of the negotiated resource is a single subframe. The main motivation behind resource partitioning is to enable cell range expansion through cell biasing. In a typical case, cell range expansion is enabled to improve system capacity, and a cell bias is applied to low-power nodes. The bias value refers to a threshold that triggers handover between two cells. A positive bias means that UE will be handed over to a picocell as soon as the difference in the signal strength from the macro- and picocells drops below a bias value. The high-power node (macro base station) informs the low-power node (pico base station) of which resources will be utilized for scheduling macro UE and which subframes would remain unutilized (almost blank subframes). This is how low-power nodes are made aware of the interference pattern from the high-power base station and can therefore schedule UE in the cell extended areas on subframes protected from high-power interference, that is, subframes corresponding to almost blank subframes at the high-power base station.

Interference coordination is performed by means of a bitmap, where each bit in the bitmap is mapped to a single subframe. The size of the bitmap is 40 bits, inferring that the interference pattern repeats itself after 40 ms. Based on the data traffic demand, the pattern can change as often as every 40 ms. The communication between nodes is peer to peer; that is, there is no formal master-slave relationship. However, the node creating dominant interference conditions effectively controls which resources can be used to serve UE in the cell range extension area. In a typical scenario, a macro base station would effectively be a master, and a pico base station is a slave since cell range expansion would most frequently be established for pico base stations. The scenario is illustrated in Fig. 5. Note that the cell range expansion may be desirable for a macro base station as well. A common use case for cell range expansion at the macro base station is to reduce the number of handovers. In a scenario with a large number of high-mobility users, the number of handovers in

The role of resource partitioning for interference management is critical in co-channel deployments. But to reach its full potential, resource partitioning needs to be paired with interference-cancellation-capable UE.

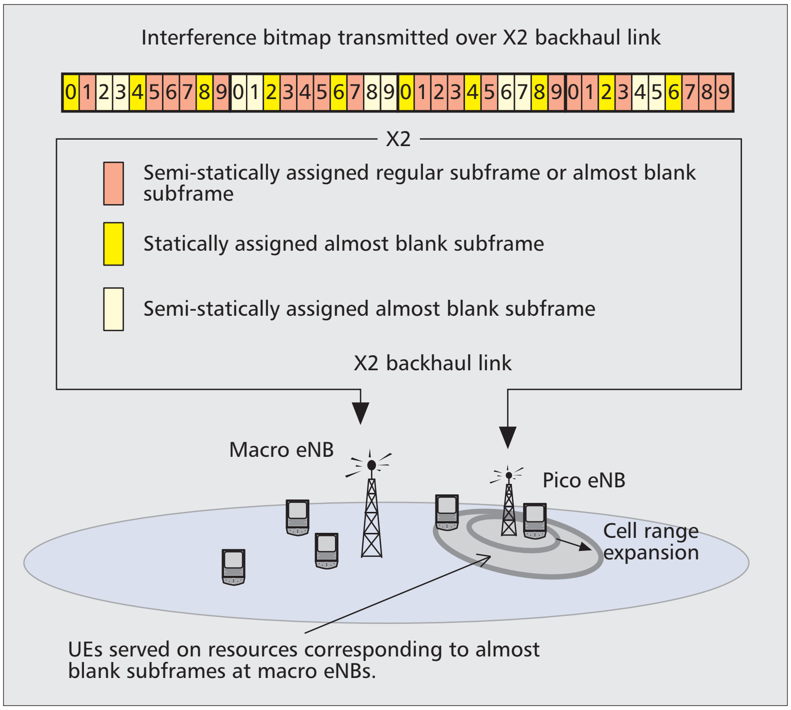


Figure 5. *Backhaul-based interference management, illustrated on a macro/pico example for FDD systems. The same mechanism can be applied for the macro/relay scenario.*

the network can become a problem, particularly when in the deployment of pico base stations the cells become small. The same resource partitioning schemes can then be utilized to allow high-mobility macro UE to remain attached to a macrocell while deep inside coverage of a picocell. In this case, the pico base station needs to restrict scheduling data traffic on some resources, allowing coverage for high-mobility macro UE.

Resource Restricted Measurements — Subframe resource partitioning creates an interference pattern that requires a new radio resource measurement paradigm. As dominant interference could potentially significantly vary from one subframe to the other, in order to ensure radio resource management measurement accuracy, it is necessary to restrict measurements to a desired set of subframes. Since the measurement configuration in LTE is not intended to change frequently, frequent changes in the resource partitioning configuration can negatively impact the measurement procedure.

For that reason, it is desirable to define *anchor* interference-protected resources that can be utilized for radio resource measurement, and the 40-bit bitmap includes indications of which subframes have *static* protection from interference and therefore are suitable for measurements. As discussed above, the remaining resources can change more often. The more resources have static interference protection, the more accurate the radio resource management measurements. However, the more resources have static interference protection, the more constrained the adaptive resource partitioning algorithm.

Closed Femto Deployments

Due to the lack of an X2 interface, only a static OAM-based solution is feasible when closed femto nodes are deployed on the same frequency as the macro network. The same principle of extending coverage of one cell into the area covered by the other can be achieved, as shown in Fig. 6. In this case, however, it is the macrocell service that needs to be extended into an area covered by the closed femtocell. Due to the static nature of the solution, however, resource partitioning cannot be adapted to the instantaneous characteristics of actual data traffic. Nevertheless, "time-of-day" type adaptation is feasible through the use of OAM.

Future Trends: Advanced UE Receiver

Co-channel deployments are of interest due to cost effectiveness and high spectral efficiency. The resource partitioning can effectively mitigate interference from the data channel. However, interference from the acquisition channels and CRS signal remains, since these signals are necessary to be transmitted for the backward compatibility reason. Subframe time shifting can be utilized in FDD systems to avoid collision of the acquisition channels between eNBs of different power classes that require partitioning, but it cannot be used in TDD systems. There is no network solution for CRS interference mitigation for either FDD or TDD systems. Without additional interference mitigation of the acquisition channels and CRS, only limited medium bias values (roughly 6–10 dB) can be supported, which limits the potential for cell range expansion.

Interference mitigation for the acquisition channels is crucial for cell range expansion. It ensures that UEs is able to detect and acquire a week cell and then measure and feedback the measurement report to the network, which is a prerequisite for handover and cell range expansion.

CRS interference mitigation has an important role in system performance. Strong CRS interference, even though present only on a relatively small fraction of resource elements, can significantly degrade turbo code performance and the overall signal-to-interference-plus-noise radio (SINR); therefore, the potential gains of cell range expansion can be severely reduced. Given that acquisition channels and CRS are all broadcast at full power targeting UE at the cell edge, a robust UE solution is feasible.

Interference Cancellation Receiver

The main rationale for the UE solution for the acquisition signals and CRS interference mitigation is that strong interference can reliably be estimated and subtracted so that in the end it does not represent significant interference at all. Acquisition channels are transmitted at the same location in all cells, which means that the acquisition channels interference consists only of the acquisition channels from the neighboring interfering cells. This structure lends itself to a design of an interference canceller, illustrated in Fig. 7a. A UE receiver first decodes the strongest signal, performs channel gain estimation toward the interfering cell, cancels the interfering signal, and continues the procedure until acquisition channels of the serving cell are acquired.

A similar procedure can be performed to remove CRS interference. The difference is that CRS tones may also interfere with data tones since interference between CRS tones between high- and low-power nodes can be avoided by CRS tone shifting. As illustrated in Fig. 7b, the procedure is similar. If strong CRS interference is detected, and after the channel gain toward the interfering cell is estimated, the CRS signal can be cancelled. The procedure is repeated until all interfering signals are subtracted.

System Performance (Macro/Pico Deployments)

An illustration of a typical performance gain that can be achieved with the heterogeneous networks with pico eNB deployments is shown in two scenarios in Figs. 8 and 9. The first scenario considers four picos randomly placed in the coverage of a macrocell and random location of users. The second scenario is a hotspot case with two picos per macrocell, randomly placed, and 2/3 of users located within 40 m radius of the two picos. CRS interference cancellation is assumed for both scenarios when resource partitioning is considered. User arrivals are modeled as a Poisson random process, and each user downloads a 1 MByte file. Biasing of 18 dB toward picocells for the resource partitioning case and 0 dB biasing when resource partitioning is not utilized are considered. Note that the results are not applicable for half duplex inband relays, since in such a scenario some resources would need to be reserved for backhaul relay communications with the DeNB. As shown in Fig. 8, for the first scenario and typical macrocell loading of 50 percent, random deployment of 4 low-power nodes can offer only a relatively modest 15 percent gain in terms of the served cell throughput. For the higher loads, close to 30 percent gain is achievable, and resource partitioning can provide an additional 44–50 percent improvement, bringing the total gain to above 90 percent for the loaded networks. These results show that in order to exploit the full potential of the deployment of picocells, it is necessary to utilize resource partitioning techniques. For a wireless network operator utilizing a byte-based charging policy, this gain directly translates into increased revenue without degrading user experience. The results for the hotspot scenario are illustrated in Fig. 9 showing even larger gains than the random user locations scenario. The total gain for the loaded networks is over 150 percent, even though only two picos are deployed per macrocell. These gains, however, can severely be reduced if CRS interference is not removed. The simulation results shown in Table 1 illustrate the impor-

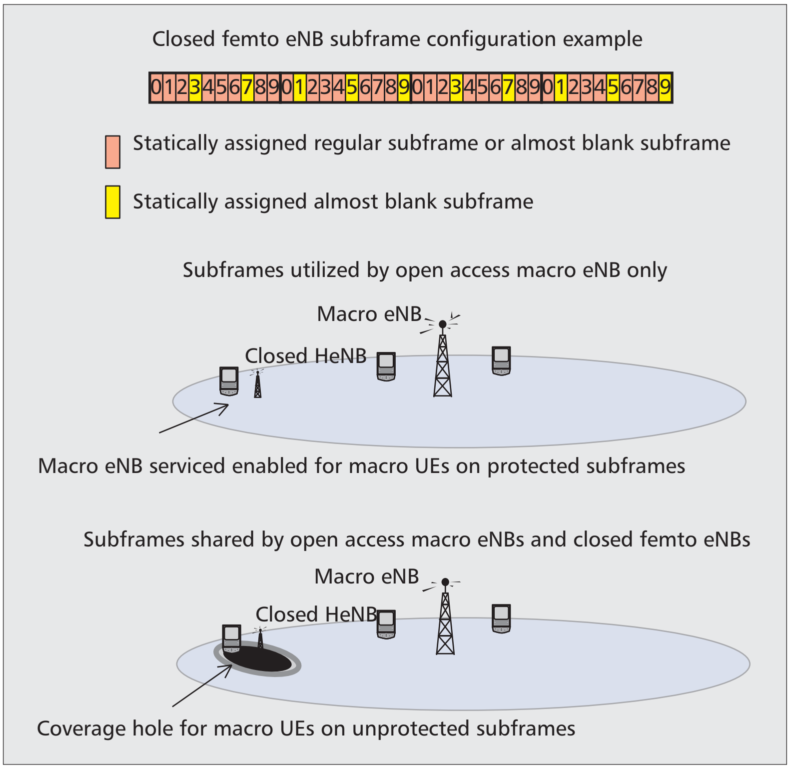


Figure 6. *Illustration of the static interference management technique for FDD systems, applicable to the macro/closed femto scenario.*

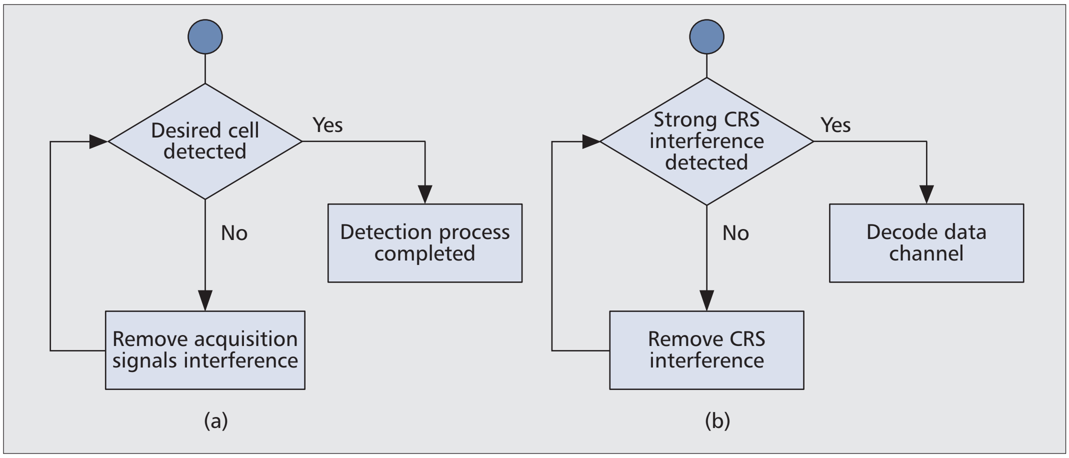


Figure 7. *Interference cancellation of acquisition signals and CRS.*

tance of CRS interference cancellation. For the considered scenario, it is estimated that even when biasing optimization is taken into account, roughly 3/4 of the gains disappear if a CRS interference canceller is not utilized.

It should be noted that the resource partitioning techniques can increase delay and jitter. However, the impact is practically negligible due to short subframe duration of 1 ms. For example, in a scenario where 50 percent of resources are unavailable due to resource partitioning, the partition can be realized with an alternating pattern where even subframes are available for scheduling and odd ones are not.

Performance summary			
Served cell throughput (gain vs. macro only/gain of resource partitioning)	Macro only	4 picos, no RP	4 picos, RP
50% Macro utilization	12.3 Mbps	14.2 Mbps (1.15x/1x)	20.5 Mbps (1.67x/1.44x)
75% Macro utilization	13.9 Mbps	17.7 Mbps (1.27x/1x)	26.6 Mbps (1.91x/1.50x)

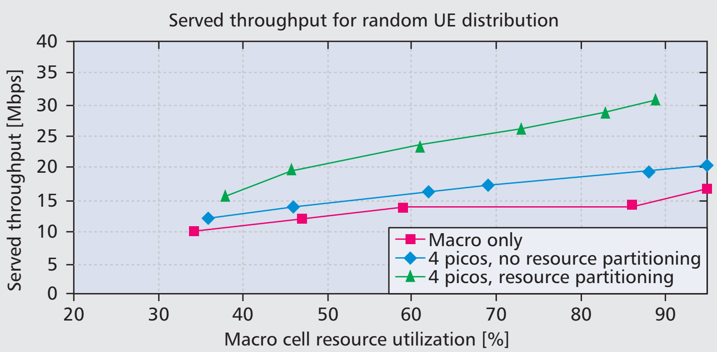


Figure 8. *Served cell throughput gains with 4 picos/macrocell — scenario 1: random UE distribution and 18 dB biasing toward picocell for resource partitioning.*

Performance summary			
Served cell throughput (gain vs. macro only/gain of resource partitioning)	Macro only	2 picos, no RP	2 picos, RP
50% Macro utilization	12.3 Mbps	16.9 Mbps (1.37x/1x)	24.2 Mbps (1.96x/1.43x)
75% Macro utilization	13.9 Mbps	21.7 Mbps (1.56x/1x)	35.8 Mbps (2.57x/1.65x)

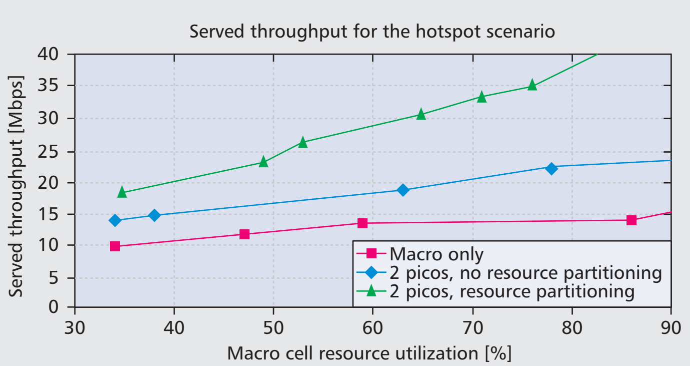


Figure 9. *Served cell throughput gains with 2 picos/macrocell — scenario 2: hotspot and 18 dB biasing toward picocell for resource partitioning.*

This partitioning pattern does not add more than 1 ms of delay and jitter; hence, there is virtually no impact on user perception even for highly delay-intolerant traffic, such as gaming or VoIP.

Conclusions

Heterogeneous deployment is seen as a pragmatic and cost-effective way to significantly enhance the capacity of LTE cellular networks. Macro nodes are used to ensure broad coverage, and low-power nodes may be located close to places with increased demand for data. Interference management represents the first crucial component of this strategy as severe interference from the macro nodes significantly limits the offloading potential of low-power nodes. Cell range expansion enabled through resource partitioning is necessary as it creates the potential for traffic load balancing, which improves the trunking efficiency of the network. The interference cancellation receiver at the UE ensures that cell acquisition channels of weak cells can be detected and CRS interference removed, fully exploiting the potential of heterogeneous network deployments. All three components are necessary to achieve the full potential of heterogeneous deployments.

References

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

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

[3] C. Patel, M. Yavuz, and S. Nanda, "Femtocells [Industry Perspectives]," *IEEE Wireless Commun. Mag.*, Oct. 2010.

[4] M. Coupechoux, J-M. Kelif, and P. Godlewski, "Network Controlled Joint Radio Resource Management for Heterogeneous Networks," *IEEE VTC Spring 2008*.

[5] W. Song, H. Jiang, and W. Zhuang, "Performance Analysis of the WLAN-First Scheme in Cellular/WLAN Interworking," *IEEE Trans. Wireless Commun.*, May 2007.

[6] H. Claussen, L.T.W. Ho, and L. G. Samuel, "Financial Analysis of a Pico-Cellular Home Network Deployment," *IEEE ICC '07*.

[7] A. Bou Saleh *et al.*, "Comparison of Relay and Pico eNB Deployments in LTE-Advanced," *IEEE VTC 2009*.

[8] T. Nihtila and V. Haikola, "HSDPA Performance with Dual Stream MIMO in a Combined Macro-Femto Cell Network," *IEEE VTC 2010*.

[9] H. R. Karimi *et al.*, "Evolution Towards Dynamic Spectrum Sharing in Mobile Communications," *IEEE PIMRC 2006*.

[10] J. Gora and T. E. Kolding, "Deployment Aspects of 3G Femtocells," *IEEE PIMRC 2009*.

[11] H. A. Mahmoud and I. Guvenc, "A Comparative Study of Different Deployment Modes for Femtocell Networks," *IEEE PIMRC 2009*.

[12] Han *et al.*, "Optimization of Femtocell Network Configuration Under Interference Constraints," *WiOPT 2009*.

[13] Y. Tokgoz *et al.*, "Uplink Interference Management for HSPA+ and 1xEVDO Femtocells," *IEEE GLOBECOM 2009*.

[14] G. Boudreau *et al.*, "Interference Coordination and Cancellation for 4G Networks," *IEEE Commun. Mag.*, 2009.

[15] A. Khandekar *et al.*, "LTE-Advanced: Heterogeneous Networks," *European Wireless Conf. 2010*.

[16] O. Simeone, E. Erkip, and S. Shamai , "Robust Transmission and Interference Management For Femtocells with Unreliable Network Access," *IEEE JSAC*, Dec. 2010.

[17] S. Annapureddy *et al.*, "http://www.ieee-ctw.org/2010/mon/Gorokhov.pdf," *2010 IEEE Commun. Theory Wksp.*, Cancun, Mexico, 2010.

[18] 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN);Overall Description; Stage 2 (Release 10).

[19] 3GPP TR 36.814, "E-UTRA; Further Advancements for E-UTRA Physical Layer Aspects."

Impact of CRS interference		
Served cell throughput at 75% loading	4 picos, RP w/o CRS IC (10 dB bias)	4 picos, RP w/ CRS IC (18 dB bias)
Gain compared to no RP	1.1x	1.44x

Table 1. *Impact of CRS interference on system performance (random user locations scenario).*

It should be noted that the resource partitioning techniques can increase delay and jitter. However, the impact is practically negligible due to short subframe duration of 1 ms.

Biographies

ALEKSANDAR D. DAMNJANOVIC (adamnjan@qualcomm.com) received his Diploma in electrical engineering from the University of Nis, Serbia, in 1994 and his D.Sc. degree in electrical engineering from George Washington University in 2000. He joined Ericsson Wireless Communications Inc., San Diego, California, in 2000, where he worked on cdma2000 base station controller development. In 2003 he joined Qualcomm Inc., San Diego, where he worked on 3G cellular standards and, since 2005, standardization and prototyping of 3GPP LTE and LTE-Advanced systems leading MAC design efforts. He is a co-author of a book, *The cdma2000 System for Mobile Communications*.

JUAN I. MONTOJO has been with Qualcomm Inc. since 1997 where he has worked as a systems engineer on different wireless systems. He has been heavily involved in the design and specification of the physical layer of LTE and is the editor of one of the PHY layer specifications (3GPP TS 36.212). He holds engineering degrees from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, and Institut Eurecom, Sophia-Antipolis, France. He also holds an M.S. from the University of Southern California (USC) and a Ph.D. from the University of California San Diego (UCSD), both in electrical engineering.

YONGBIN WEI received B.E. and M.S. degrees from the University of Science and Technology of China, and a Ph.D. degree from Purdue University, all in electrical engineering. Since he joined Qualcomm in 2000, he has worked on system design, evaluation, and standardization for cdma2000 and 1xEV-DO as well as base station ASIC chip development. Since 2006 he has been leading the system efforts for system design, standardization, and prototype of LTE and LTE-Advanced. He has 52 U.S. issued patents and many more pending.

TINGFANG JI received his B.S. degree in electronic engineering from Tsinghua University, China, in 1995, his M.S and Ph.D degrees, both in electrical engineering, from the University of Toledo, Ohio, and the University of Michigan, Ann Arbor in 1997 and 2001, respectively. From 2001 to 2003 he was a member of technical staff in the Bell Laboratories Advanced Technology Department involved in cellular technologies and ultra wideband research. Since 2003 he has been with the Corporate R&D division of Qualcomm Inc., where he is currently a senior staff engineer and manager. From 2003 to 2007 he was one of the key technical contributors to the development of wideband OFDMA technologies that evolved into IEEE 802.20 and 3GPP2 UMB standards. Since 2007 he has been actively contributing to the development and standardization of 3GPP LTE-Advanced technology. His research interests include the PHY/MAC/RF aspects of heterogeneous networks, carrier aggregation, network MIMO, and relay networks.

MADHAVAN VAJAPEYAM received his B.S. degree in electrical engineering from the Universidade Federal da Paraiba, Campina Grande, Brazil, in 2000, and M.S. and Ph.D. degrees in electrical engineering from USC, Los Angeles, in 2002 and 2007, respectively. Since 2007 he has been with the Corporate R&D division of Qualcomm Inc., where he is actively involved in the development and standardization of next-generation 3GPP LTE and LTE-Advanced technologies. His research interests include algorithms for physical and MAC layer design of wideband OFDMA systems, interference management in heterogeneous networks, and MIMO communications.

TAO LUO received his Ph.D. in EECS from the University of Toronto, Canada, in June 2001. From July 2001 to October 2004, he was with Wireless Design Center of Texas Instruments, San Diego, and worked on a WCDMA related project and was a key contributor to the WCDMA baseband and RF chipset development. Since November 2004 he has been with the Standards group and later Corporate R&D at Qualcomm. He has actively contributed to the standardization of HSUPA, LTE, and, more recently, LTE-Advanced. Since 2008 he has been leading the LTE Rel-8 and then LTE-A UE prototyping for HetNet. He has over 100 issued or pending U.S. patents in the area of wireless communications.

TAESANG YOO received his B.S. degree (Hons.) in electrical engineering from Seoul National University, Korea, in 1998, and M.S. and Ph.D. degrees in electrical engineering from Stanford University in 2003 and 2007. Since 2006 he has been with Corporate R&D, Qualcomm, Inc., where he is currently working on 3GPP LTE and LTE-Advanced wireless systems. His research interests include multiple antenna systems, communications and information theory, heterogeneous cellular networks, and various design and performance aspects of LTE/LTE-A systems and standards.

OSOK SONG received his B.S. and Ph.D. in electrical engineering from Seoul National University. He joined Samsung Electronics in 2003 and has been involved in 3GPP standardization. He served as vice chairman of 3GPP SA2, the working group responsible for 3GPP network architecture, and rapporteur (editor) of several work items. In April 2007 he joined Qualcomm Inc., and worked on LTE and LTE-Advanced network protocol research and standardization. He is an active participant in 3GPP RAN3, the working group responsible for 3GPP radio network architecture and protocols.

DURGA MALLADI received his B.Tech (1993) degree from the Indian Institute of Technology, Madras, and M.S. (1995) and Ph.D. (1998) degrees from the University of California, Los Angeles. He joined Qualcomm in 1998 and worked on system design and implementation of Globalstar from 1998 to 2001. From 2001 to 2004 he led the system design and standardization of 3GPP HSDPA and HSUPA. From 2004 onward he has led the research and development activities related to LTE and LTE Advanced, including system design, standardization, implementation, and testing. His research interests include MIMO, signal processing techniques, communication theory, and cognitive radio.