CHAPTER

HETEROGENEOUS DEPLOYMENTS

14

The continuous increase in traffic within mobile-broadband systems and an equally continuous increase in terms of the data rates requested by end users will impact how cellular networks are deployed in the future. In general, providing very high system capacity (traffic volume per area unit) and very high per-user data rates will require a densification of the radio-access network, that is, the deployment of additional network nodes (or transmission/reception points). By increasing the number of nodes, the traffic per area unit can be increased without requiring a corresponding increase in the traffic that needs to be supported per network node. Also, by increasing the number of network nodes, the base-station-to-device distances will, in general, be shorter, implying a link-budget improvement and a corresponding improvement in achievable data rates.

As illustrated at the top of Figure 14.1, uniform densification of the macro cell layer, that is, reducing the coverage area of each cell and increasing the total number of macro-cell sites,[1] is a path that has already been taken by many operators. As an example, in many major cities the distance between macro-cell sites is less than a few hundred meters in many cases.

An alternative or complement to a uniform densification of the macro layer is to deploy additional lower-power nodes, or "small cells", under the coverage area of the macro layer, as illustrated at the bottom of Figure 14.1. In such a *heterogeneous deployment*, the low-power nodes[2] provide very high traffic capacity and improved service experience (higher end-user throughput) locally—for example, indoor and outdoor hot-spot positions—while the macro layer provides full-area coverage. Thus, the layer with low-power nodes (pico nodes) can also be referred to as providing *local-area access*, in contrast to the wide-area-covering macro layer.

The idea of heterogeneous, or multilayer, deployments is in itself not new; "hierarchical cell structures" have been used since mid-1990s. However, with extensive use of mobile broadband, the interest in heterogeneous deployments as a means to increase capacity and end-user data rates has increased significantly.

It is important to point out that the use of low-power nodes as a complement to a macro network is a deployment strategy, not a technology component, and as such is already possible in the first release of LTE. Nevertheless, LTE releases 10 and 11 provide additional

[1]Here, a macro node is defined as a high-power node with its antennas typically located above rooftop level.
[2]The term "pico node" is used to denote a low-power node, typically with the antennas located below rooftop level.

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00014-5

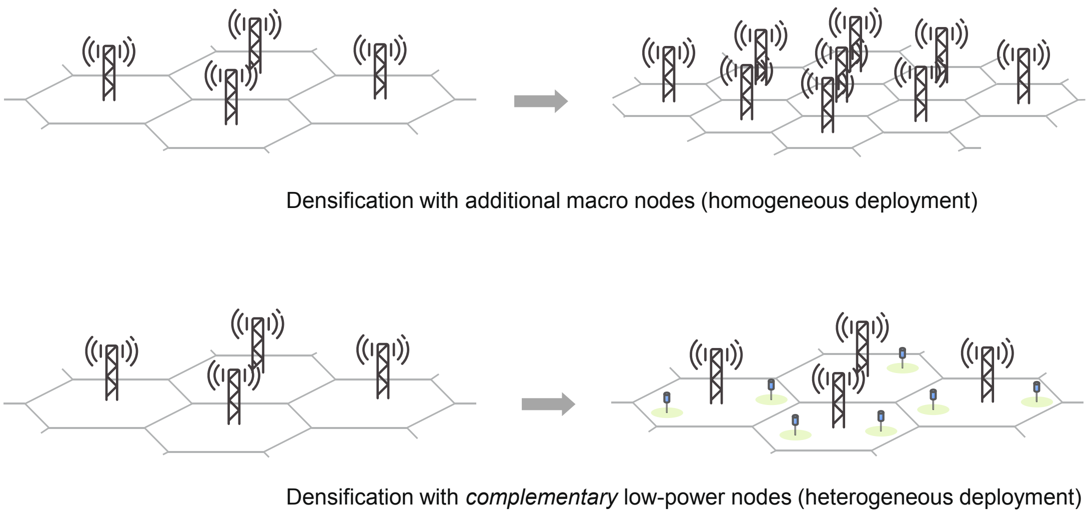

FIGURE 14.1

Homogeneous versus heterogeneous densification.

features improving the support for heterogeneous deployments, in particular in the area of handling interlayer interference.

14.1 INTERFERENCE SCENARIOS IN HETEROGENEOUS DEPLOYMENTS

One distinctive property of a heterogeneous deployment is the large difference in transmit power between the overlaid macro layer and the underlaid pico layer. Depending on the scenario, this may result in significantly more complex interference scenarios compared to a homogeneous network, more specifically interference between the layers. *Interlayer interference handling* is therefore a crucial aspect in most heterogeneous deployments.

If different frequency resources, in particular different frequency bands, are used for different layers, the interlayer interference can be avoided. Frequency separation is also the traditional way of handling interlayer interference in, for example, GSM where different carrier frequencies are used in the different layers. However, for a wideband radio-access technology such as LTE, using different carrier frequencies for different layers may lead to an undesirable spectrum fragmentation as discussed in the previous chapter. As an example, for an operator having access to 20 MHz of spectrum, a static frequency separation between two layers would imply that the total available spectrum had to be divided, with less than 20 MHz of spectrum being available in each layer. This could reduce the maximum achievable data rates within each layer. Also, assigning a substantial part of the overall available spectrum to a layer during periods of relatively low traffic may lead to inefficient spectrum utilization. Thus, with a wideband high-data-rate system such as LTE, it should preferably be possible to deploy a multilayered network with the same spectrum being available in all layers. This is in line with the motivation for single-frequency reuse in Chapter 13. Nevertheless, separate spectrum allocation for the two layers is a relevant scenario, especially if new spectrum becomes available at very high frequencies, less suitable for wide-area coverage. Furthermore, frequency-separated deployments imply that the duplex scheme can be chosen independently between the layers, for example, using FDD in the wide-area macro layer and TDD in the local-area pico layer.

Simultaneous use of the same spectrum in different layers implies interlayer interference. The characteristics of the interlayer interference depend on the transmission power in the respective layer, as well as in the node-association strategy used.

Traditionally, node association or cell association, that is, determining which network point the device should be connected to, is based on device measurements of the received power of some downlink signal—more specifically, the cell-specific reference signals in the case of LTE. Based on the device reporting those measurements to the network, the network decides whether a handover should take place or not. This is a simple and robust approach. In homogeneous deployments with all transmission points having the same power, downlink measurements reflect the uplink path loss and downlink-optimized network-point association is also reasonable from an uplink perspective. However, in a heterogeneous deployment, this approach can be challenged due to the large difference in transmission power between the layers. In principle, the best uplink reception point is not necessarily the best downlink transmission point, implying that uplink and downlink points ideally should be determined separately [83]. For example, downlink point selection could be based on received signal strength, while uplink point selection preferably is based on the lowest path loss. This is illustrated in Figure 14.2 where the "cell border" is

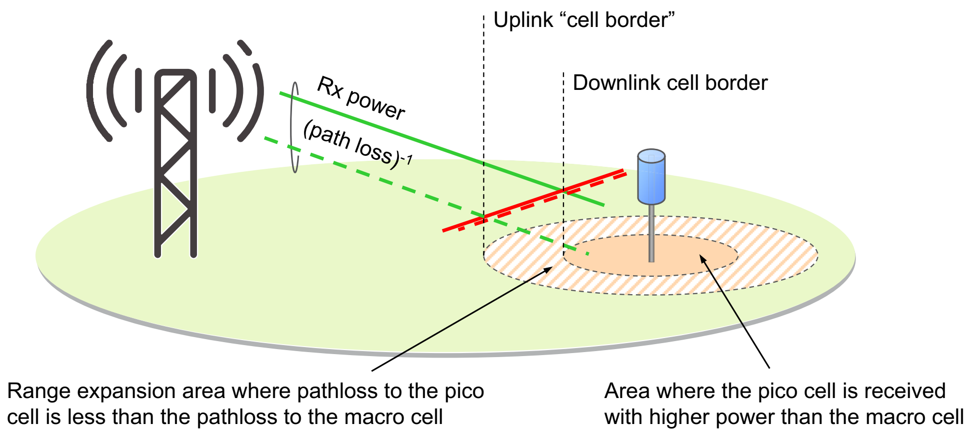

FIGURE 14.2

Illustration of high-interference area in a heterogeneous network deployment with range expansion.

different for uplink and downlink. However, since there are tight and time-critical dependencies between the uplink and downlink—for example, in the form of hybrid-ARQ acknowledgments transmitted in the downlink as a result of receiving uplink transmissions—the two links are in practice terminated in the same node.[3] Node association is therefore a compromise between the best choice from an uplink and downlink perspective.

From a single link perspective, associating the device with the transmission point with the highest received power implies that the device is often connected to a higher-power macro point even if the path loss to a pico point is significantly smaller. This will not be optimal from an uplink coverage and capacity point of view. It should also be noted that, even in terms of downlink system efficiency, it may not be optimal to select the transmission point with the highest received power in a heterogeneous network deployment. Although transmissions from the macro point are received with higher power than from a pico point, this is at least partly due to the higher transmit power of the macro point. In that case, transmission from the macro point is associated with a higher "cost" in terms of interference to other cells. Expressed alternatively, a transmission from the macro point will prohibit the use of the same physical resource in *any* of the underlaid pico points.

Alternatively, at the other extreme, node association could be based solely on estimates of the (uplink) path loss. In practice this can be achieved by applying an offset to the received-power measurements used in conventional cell association, an offset that would compensate for the difference in transmit power between different transmission points. Such an offset is supported by LTE already from the first release and possible to configure on a per-device basis. By using an offset in the node-association strategy, the area in which a pico point is selected is extended as illustrated in Figure 14.2. This is sometimes referred to as *range expansion*.

Selecting the network point to which the path loss is the smallest, that is, applying a large degree of range expansion, would maximize the uplink received power/SINR, thus maximizing the achievable uplink data rates. Alternatively, for a given target received power, the device transmit power, and thus the interference to other cells, would be reduced, leading to higher overall uplink system efficiency. Additionally, it could allow for the same downlink physical resource to be used by other pico points also, thereby improving downlink system efficiency.

However, due to the difference in transmit power between the transmission points of the different deployment layers, downlink transmissions from the macro point will be received with substantially higher power in the range expansion area (illustrated by the dashed region in Figure 14.2) than the actual desired downlink transmission from the pico point. Within this

[3]The downlink transmission point and the uplink reception point could be geographically separated if remote antennas are used, see further Section 14.5.

area, there is thus potential for severe downlink inter-cell interference from the macro point to devices receiving transmissions from a pico point. The interference has both a static load-independent component stemming from the cell-specific reference signals (CRS), synchronization signals (PSS, SSS) and system information (PBCH), and a dynamic load-dependent component stemming from data transmissions (PDSCH) and control signaling (PCFICH, PHICH, PDCCH, and EPDCCH).

The interference from PDSCH transmissions in the macro layer to lower-power PDSCH transmissions from a pico point can be relatively straightforwardly handled by scheduling coordination between the nodes according to the same principles as inter-cell interference coordination described in Section 13.1. As an example, an overlaid macro point could simply avoid high-power PDSCH transmission in resource blocks in which a device in the range expansion region of a pico point is to receive downlink data transmission. Such coordination can be more or less dynamic depending on to what extent and on what time scale the overlaid and underlaid nodes can be coordinated. The same coordination as for the PDSCH could also be applied to the EPDCCH. It should also be noted that, for a pico-network point located on the border between two macro cells, it may be necessary to coordinate scheduling between the pico point and both macro cells.

Less obvious is how to handle interference due to the macro-node transmissions that cannot use dynamic inter-cell interference coordination, such as the L1/L2 control signaling (PDCCH, PCFICH, and PHICH). Within a layer, for example, between two macro nodes, interference between such transmissions is not a critical issue as LTE, including its control channels, has been designed to allow for one-cell frequency reuse and a corresponding SIR down to and even below −5 dB. This inherent robustness allows for moderate range expansion, in the order of a couple of dB. In many scenarios this amount of range expansion is adequate and further increasing it would not improve performance, while in other scenarios a larger amount of range expansion may be useful. Using a large amount of range expansion can result in a signal-to-interference ratio that is too low for the control channels to operate correctly, calling for means to handle this interference situation. Note that the usefulness of range expansion is highly scenario dependent. One simplistic example where range expansion may not be useful is illustrated in the right part of in Figure 14.3 where the building walls provide isolation between the two cell layers.

In the following sections, four different approaches to heterogeneous deployments are described:

- Release 8 functionality, using features available in the first release of LTE to support a medium amount or range expansion. No inter-cell time synchronization or coordination is assumed.
- Frequency-domain partitioning, where an extensive amount of range expansion is supported through interference handling in the frequency domain, for example, by using carrier aggregation.

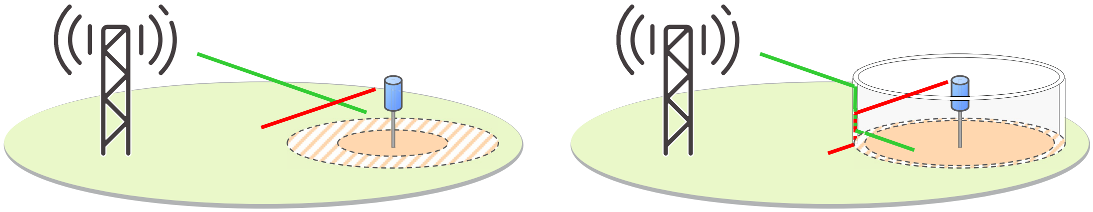

FIGURE 14.3

Illustration of range expansion in different scenarios.

- Time-domain partitioning, where an extensive amount of range expansion is supported through interference handling in the time domain.
- So called "Shared cell", using CoMP techniques from Chapter 13 to support a large amount of range expansion.

In the first three of these approaches, each transmission point defines a unique cell, that is, it has a unique cell identity and transmits all signals associated with a cell such as cell-specific reference signals and system information. The last approach differs in this respect as a transmission point does not necessarily define a unique cell. Instead, *multiple* geographically separated transmission points may belong to the same cell.

Finally, note that all schemes except the first assumes interlayer coordination and time-synchronization across (neighboring) transmission points.

14.2 HETEROGENEOUS DEPLOYMENTS USING REL-8 FUNCTIONALITY

Heterogeneous deployments are already possible from the first release of LTE using release 8 functionality. In this case, the transmission points define unique cells and point association, or cell selection, is typically based on the downlink received power as in the homogeneous case. Despite being simple—for example, there is no need for inter-cell time synchronization or inter-cell coordination—a fair amount of range expansion, up to several dBs, is easily achieved in this scheme by adjusting the cell selection offset. The amount of macro interference naturally limits the amount of range expansion possible, but the amount of range expansion possible is sufficient for many scenarios. Additional tools available in release 8 to obtain a fair amount of range expansion include PDCCH power boosting in the pico cell, fractional loading of the PDCCH in the overlaid macro cell to reduce interference, and adjusting the PDCCH operating point in terms of PDCCH error probability.

It is also worth pointing out that, in many scenarios, most of the gains are obtained by simply deploying the pico nodes with no or only a small amount of range expansion. However, in some specific scenarios, a larger amount of range expansion may be useful, calling for some of the schemes discussed later.

14.3 FREQUENCY-DOMAIN PARTITIONING

Frequency-domain partitioning attempts to reduce interference by using different parts of the frequency spectrum for different layers. The transmission points define unique cells and measurements of the received downlink power are used as the basis of point association or, equivalently, cell selection.

The simplest case is a static split, using different and nonoverlapping pieces of spectrum in the macro and pico layers as illustrated in Figure 14.4. Although simple, such a scheme suffers from not being able to dynamically reallocate resources between the layers to follow instantaneous traffic variations.

A more dynamic approach for handling the downlink interlayer interference in the range-expansion zone in case of a large amount of range expansion is to use carrier aggregation in combination with cross-carrier scheduling as outlined in Chapter 10. The basic idea is to split the overall spectrum into two parts through the use of two downlink carriers, f_1 and f_2, as illustrated in Figure 14.4 but without the loss of flexibility resulting from a static split.

In terms of data (PDSCH) transmission, both carriers are available in both layers and interference between the layers is handled by "conventional" inter-cell interference coordination (see Section 13.1). As already mentioned, such interference coordination can be more

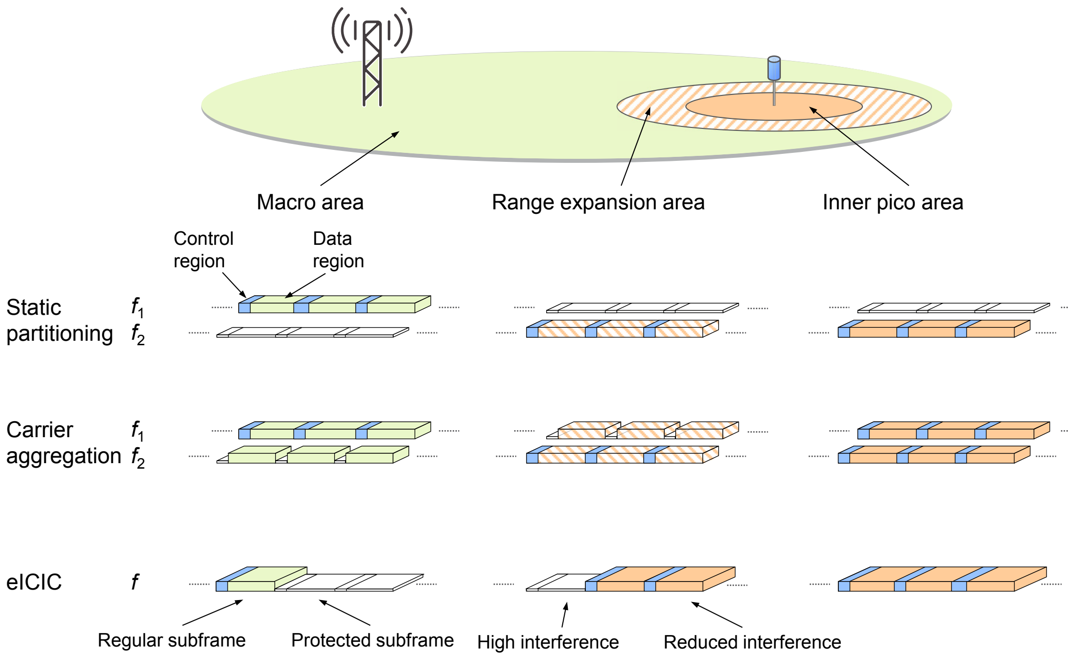

FIGURE 14.4

Frequency-domain and time-domain partitioning.

or less dynamic depending on the time scale on which the layers can be coordinated. Also, the possibility for carrier aggregation allows for both carriers, that is, the total available spectrum, to be assigned for transmission to a single device. Thus, at least for carrier-aggregation-capable devices, there is no spectrum fragmentation in terms of data (PDSCH) transmission. Legacy devices, on the other hand, will experience peak rates from a single carrier only. This may be an issue for an operator with a large fleet of legacy devices.

On the other hand, in terms of L1/L2 control signaling (PCFICH, PHICH, and PDCCH), there is at least partly a more semi-static frequency separation between the layers. More specifically, the macro layer should avoid high-power transmission within the control region on carrier f_1. Assuming a time-synchronized network, interference to the control region of the pico layer is reduced on this carrier and the pico cells can use the carrier for control signaling to devices in the range expansion region. Due to the possibility for cross-carrier scheduling, DL-SCH transmission can still be scheduled on both carriers, as well as an aggregation of these, subject to dynamic interlayer interference coordination even if the macro cell only transmits control signaling on carrier f_1. The same is true for a pico cell; even if the pico cell can only use carrier f_2 for transmission of scheduling assignments to devices in the range-expansion zone, DL-SCH transmissions can still be scheduled on both carriers.

It should be noted that, for devices in the inner part of a pico cell, carrier f_1 could also be used for L1/L2 control signaling. Similarly, macro cells could use also carrier f_2 for control signaling, assuming a reduced transmit power is used. Thus, the macro cell could use carrier f_2 for lower-power control signaling, for example, for devices close to the corresponding macro-transmission point.

In the preceding discussion, PDCCH has been assumed, but the EPDCCH can equally well be used. In principle, the EPDCCH can be subject to the same inter-cell interference coordination scheme as the PDSCH. This could be used to support large amounts of range expansion without carrier aggregation. In this case, the macro and pico layers simply use different sets of physical resource-block pairs, coordinated in a more or less dynamic manner. However, note that the EPDCCH is limited to the device-specific search spaces only. Consequently, the PDCCH is needed for scheduling, for example, of system information.

Finally, note that the (cell-specific reference) signals used by the device to maintain synchronization with the pico cell in the range expansion zone are subject to interference from the macro layer. How well the device can handle this will put an upper limit to the amount of range expansion possible. Hence, to fully exploit the benefits of range expansion, interference cancelling receivers are needed in the devices.

14.4 TIME-DOMAIN PARTITIONING

An alternative to frequency-domain partitioning is to use time-domain partitioning as illustrated at the bottom of Figure 14.4. In 3GPP, this is known as *(further) enhanced inter-cell interference coordination*, (F)eICIC. Work on eICIC started in release 10 and was finalized in release 11 under the name of FeICIC. Also in this case the transmission points correspond to separate cells, hence the FeICIC name used in 3GPP.

The basic idea with time-domain partitioning is to restrict the transmission power of the overlaid macro cell in some subframes. In these *reduced-power subframes* (or *almost blank subframes*), devices connected to the pico cell will experience less interference from the overlaid macro cell for both data and control. From a device perspective they serve as *protected subframes*. The pico cell can therefore schedule devices in the range expansion area using the protected subframes and devices in the inner part of the pico cell using all subframes. The macro cell, on the other hand, primarily schedules devices outside the protected subframes (see Figure 14.5 for an illustration). The gain from deploying the pico cells must be larger than the loss incurred by the macro cell reducing power in some subframes for the time-domain partitioning scheme to be attractive. Whether this holds or not is highly scenario dependent although using a reduced but nonzero transmission power in the macro cell for the protected subframes to limit the resource loss in the macro layer is often advantageous.

To support time-domain partitioning in a heterogeneous network, signaling of *protected-subframe patterns*, that is, information about the set of protected subframes, is supported between eNodeBs of different layers using the X2 interface. Note that the set of protected subframes could be different in different cells and more or less dynamic, once again depending on the time scale on which the deployment layers can be coordinated.

It should be noted that the macro cell must not necessarily avoid control-signaling transmission completely in the protected subframes. In particular, it could be beneficial to retain the possibility for a limited amount of control signaling related to uplink transmissions, for example, a limited amount of uplink scheduling grants and/or PHICH transmission, in order to not cause too much impact on the uplink scheduling. As long as the macro-cell control-signaling transmissions are limited and only occupy a small fraction of the overall control region, the interference to devices in the range expansion region of the pico cell could be kept at an acceptable level. However, the signaling of protected-subframe patterns is also

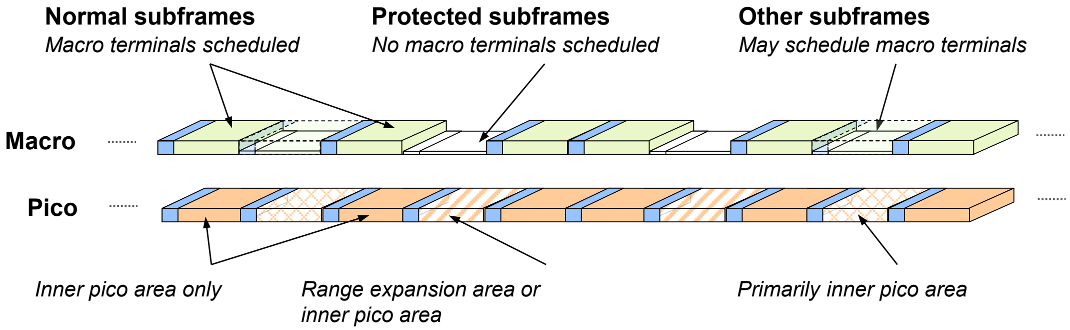

FIGURE 14.5

Protected subframes.

defined so that impact on the uplink scheduling is minimized even if no uplink scheduling grants and PHICH can be transmitted in protected subframes. This is achieved by having the protected-subframe patterns matched to the eight-subframe timing of the uplink hybrid-ARQ protocol. It should be noted that this implies that the pattern is not aligned to the 10 ms frame but only to a 40-ms four-frame structure for FDD. For TDD the periodicity also depends on the uplink−downlink configuration.

Up to four different patterns can be exchanged between eNodeBs: two patterns for scheduling and CSI measurement purposes, one pattern for RRM measurements in the serving cell, and one pattern for RRM measurements in neighboring cells. The purpose of having two patterns for CSI measurements is to handle load variations between macro- and pico layers without frequent reconfigurations of the devices as is further discussed later (see Figure 14.6 for an illustration). In case of a high load in the range expansion area, which is the case at time t_1 in the figure, it may be beneficial to have a relatively large number of protected subframes to allow these devices to be served by the pico cell. At a later time instant, t_2 in the figure, the majority of the devices have moved from the range expansion area into the macro area, calling for a reduction of the number of protected subframes. Thus, by varying the size of the set of currently protected subframes, the configurations can be adjusted to match changes in the scenario. At the same time, there must be a set of subframes that are always protected in order for the pico cell to be able to contact a device in the range expansion area as the connection to a device otherwise might be lost. Therefore, exchange of two subframe patterns are supported on X2, one which is intended to be used for the *currently* protected subframes and one for the *always* protected subframes. The intention is to use the former for scheduling coordination across the cells, allowing for relatively frequent updates, while the latter is updated infrequently and used as the basis for configuring protected subframes in the devices as described later. Subframes belonging to neither of the two sets earlier can be thought of as “never protected” subframes.

Clearly, the interference experienced by devices connected to the pico cell may vary significantly between protected and nonprotected subframes. Thus, CSI measurements carried out jointly on both the protected and nonprotected subframes will not accurately reflect the interference of either type of subframes. To address this issue, the device is provided with information about the protected subframes via dedicated RRC signaling using similar bitmaps as described earlier.[4] Two bitmaps can be sent to the device, one defining the sets of *protected* subframes and one defining the set of *highly interfered* subframes. Preferably, the protected and highly interfered subframes correspond to the always-protected and never-protected subframes derived from the X2 signaling shown earlier. The remaining subframes, if any, not belonging to either of these two subsets have a more unpredictable interference situation as the macro may or may not use reduced power.

[4]Note that transmission mode 10 with multiple CSI processes can be used as an alternative to the two bitmaps.

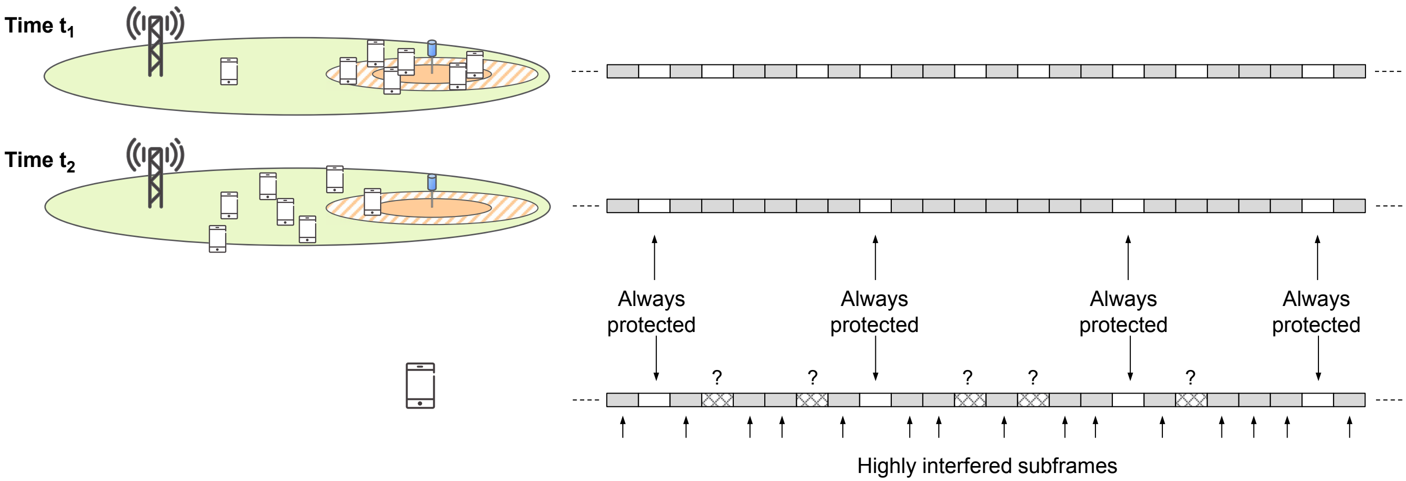

FIGURE 14.6

Exchange of subframe patterns between macro and pico nodes and the corresponding configuration in the device.

CSI reporting is carried out individually for the two subsets. Which subset a certain CSI report reflects depends on in which subframe the CSI is transmitted; the CSI reflects the interference situation in the subset to which the subframe belongs. Hence, the device should only average interference measurements during subframes belonging to the same subset. A CSI report transmitted in a subframe not belonging to either of the subsets is undefined from an interference measurement perspective. Through the use of two subsets, the network can predict the radio-channel quality for upcoming transmissions, irrespective of whether they occur in protected subframes or not.

Having two subsets is beneficial for multiple reasons. One example is the situation outlined above, where the set of protected subframes varies over time. Frequent updates of the configurations in all the affected devices may not be feasible with reasonable overhead. Instead, measuring CSI on a subset of subframes that are always protected is typically preferred as it allows the network to dynamically use reduced power and schedule devices in the range expansion zone in additional subframes without reconfiguring all the devices. CSI reports reflecting the situation in the protected subframes are then used for link adaptation in the range expansion zone, while CSI reports from the highly interfered subframes are useful when scheduling devices in the inner pico area. Another example is when a pico cell is located at the border between, and subject to interference from, two macro cells. If the macro cells have differently configured and only partly overlapping sets of protected subframes, the pico-cell scheduling as well as the configuration of the CSI measurement sets need to take the structure of the protected sets of both macro cells into account.

The discussion so far has focused on the dynamic part of the interference, that is, the interference part that varies with the traffic load and can be handled by ICIC and time-domain partitioning. However, there is also static interference from the macro cell in the range expansion area. For example, cell-specific reference signals, synchronization signals, and the PBCH still need to be transmitted. To support extensive range expansion, despite the presence of these signals and channels, the interfering signals need to be cancelled. Therefore, cancellation of CRS, PSS/SSS, and PBCH is required to fully exploit the features described previously—functionality that is not mandated in release 10. To assist the device in cancelling the interference, RRC signaling provides information about the physical-layer identity of the neighboring cells, the number of antenna ports in those cells, and the MBSFN configuration (MBSFN configuration is needed as there is no CRS in the data region in those subframes).

Time-domain partitioning is supported in RRC_CONNECTED only. Idle devices will still be able to connect to the pico cell, but cannot exploit range expansion until they enter RRC_CONNECTED.

14.5 SHARED CELL

In the partitioning schemes described in the previous sections, the transmission points correspond to individual cells, each of which has an individual cell identity that is different

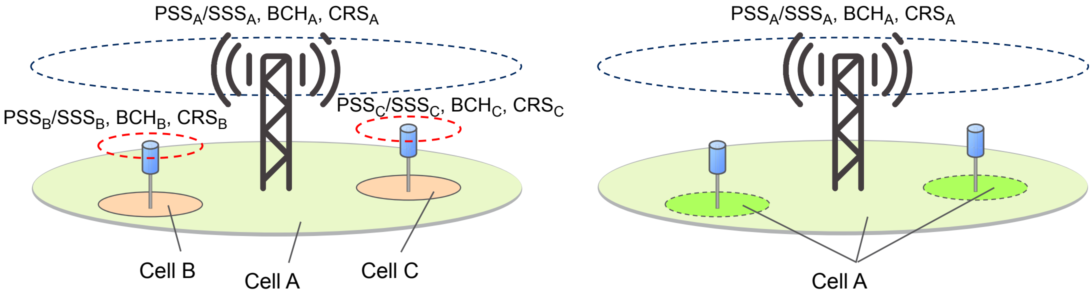

FIGURE 14.7

Independent cells (left) versus shared cell (right).

from neighboring cells in either of the network layers. Consequently, each pico node transmits unique system information, synchronization signals, and cell-specific reference signals. This is illustrated on the left in Figure 14.7.

Alternatively, CoMP techniques (see Chapter 13) can be used to realize heterogeneous deployments. To understand this approach, remember the distinction between a *cell* and *transmission point*. A cell has a unique physical-layer cell identity from which the position of the cell-specific reference signals is derived. By acquiring the cell identity, a device can determine the CRS structure of the cell and receive system information necessary to access the network. A transmission point, on the other hand, is in this context simply one or more colocated antennas from which a device can receive data transmissions.

By exploiting the DM-RS introduced in release 10, the PDSCH does not have to be transmitted from the same point as the cell-specific reference signals. Data can instead be transmitted from one of the pico transmission points when beneficial and the time—frequency resources can be reused between spatially separated pico transmission points. Since the pico-transmission points neither transmit (unique) cell-specific reference signals, nor system information, they do not define cells but are part of the overlaid macro cell. This CoMP approach to heterogeneous deployments is therefore commonly referred to as *shared-cell ID*, illustrated on the right in Figure 14.7.

In Figure 14.8, data is transmitted to device number two from the rightmost transmission point. Since the associated DM-RS is transmitted from the same transmission point as the data, the point used for data transmission does not need to be known by the device. Spatial reuse gains, that is, reusing the time—frequency resources used for the data transmission across multiple pico nodes within the same macro cell, are hence obtained similarly to the resource-partitioning schemes described in the previous sections.

The control information required in release 10 is based on CRS and the control information therefore needs to be transmitted from (at least) the macro site as is the case for the first device in Figure 14.8. Thus, in many cases, data and the associated control signaling originates from *different* transmission points. This is in theory transparent to the device; it

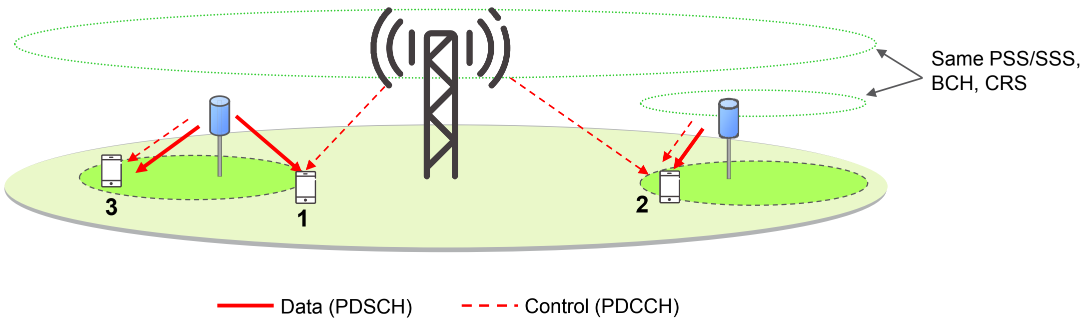

FIGURE 14.8

Heterogeneous deployment using shared cell.

only needs to know which reference signal to use for which piece of information but not from which transmission point the information originate. The quasi-colocation mechanism introduced in release 11 (see Chapter 5) is preferably used to ensure that the device only exploits the relevant reference signals.

In Figure 14.8, multiple ways of transmitting the control information are illustrated. The first case, involving device 1 with control signaling originating from the macro site only, has already been described. Alternatively, identical CRS and control channels can be transmitted from the macro *and* the pico node as shown for device 2. To the device this will appear as one composite node as the *same* signal is transmitted from both nodes. The first case is beneficial from a network power-consumption perspective as the pico-transmission point is active only when there is data to transmit. The second case, on the other hand, provides an improvement in the signal-to-noise ratio for the control signaling via over-the-air combining of the macro and pico transmissions. Furthermore, as an LTE device estimates the uplink path loss for power control purposes from the received CRS signal strength (see Chapter 7 for a discussion on uplink power control), the second case can sometimes result in a more accurate uplink power control.

In both these cases there is no spatial-reuse gain for the control signaling as the macro site is involved in all these transmissions and time–frequency resources cannot be reused across pico nodes. This can be addressed by using the DM-RS-based EPDCCH for control signaling and transmitting it from the same node as used for the PDSCH as is the case of the third device in Figure 14.8.

Devices not supporting DM-RS-based transmission can still operate in the shared-cell scheme. Data transmissions to these devices are CRS-based and thus handled in the same manner as the PDCCH control signaling described previously. Although no spatial reuse gain will be possible for these devices, they will benefit from the pico nodes through an improved signal-to-noise ratio.

Channel-state feedback used for scheduling decisions is preferably based on the CSI-RS. Different pico nodes, as well as the macro node, can be configured to use different and noninterfering CSI-RS configurations to allow devices to estimate the channel conditions to the transmission points corresponding to the different nodes. For devices not supporting CSI-RS, the channel-state feedback is based on the CRS. In these cases, the eNodeB may need to scale the received reports to account for the difference in the set of transmission points used for CRS and PDSCH.

Deploying a shared-cell scheme can be done by connecting one or multiple remote radio units (RRUs) as well as the macro site to the same main unit using optical fibers. One reason for this is the tight coupling between the macro and pico nodes with control and data originating from different transmission points, calling for low-latency connections.

Centralization of the processing provides benefits also in terms of uplink performance and, in many cases, this alone can motivate the usage of RRUs with centralized processing. Any combination of transmission points, not necessarily those used for downlink transmission to a device, can be used for receiving the transmissions from that device. By combining the signals from the different antennas in a constructive manner at the central processing node—in essence, uplink CoMP (see Chapter 13)—a significant improvement in the uplink data rates can be achieved. In essence, uplink reception and downlink transmission have been *decoupled* and it is possible to do "uplink range expansion" without causing a downlink interference problem as in separate-cell-ID deployments. The uplink gains can be achieved also for release 8 devices.

Heterogeneous deployments using shared cells can also provide additional mobility robustness compared to deployments with separate cells. This can be an important aspect, especially when moving from a pico node to the macro node. In a separate-cell deployment, a handover procedure is required to change the serving cell. If, during the time it takes to perform the handover procedure, the device has moved too far into the macro area, it may drop the downlink connection from the pico node before the handover is complete, leading to a radio-link failure. In a shared-cell deployment, on the other hand, the transmission point to use for downlink transmission can be rapidly changed *without a handover procedure*. Thus, the probability of dropping connections is reduced.

14.6 CLOSED SUBSCRIBER GROUPS

The discussion in the previous sections assumes that the devices are allowed to connect to the low-power pico node. This is known as *open access* and typically the low-power nodes are operator-deployed in such a scenario. Another scenario, giving rise to a similar interference problem, is user-deployed home base stations. The term *closed subscriber groups* (CSG) is commonly used to refer to cases when access to such low-power base stations is limited to a small set of devices, for example the family living in the house where the home base station is located. CSG results in additional interference scenarios. For example, a device located close to but not permitted to connect to the home base station will be subject to strong interference and may not be able to access the macro cell. In essence, the presence of a home base station may cause a coverage hole in the operator's macro network, a problem that is particularly worrisome as the home base stations typically are user deployed and their locations are not controlled by the operator. Similarly, reception at the home base station may be severely impacted by uplink transmissions from the device connected to the macro cell. In principle, these problems can to some extent be solved by the same means as mentioned earlier—by relying on interference coordination between the scheduling in the home-eNodeB layer and an overlaid macro. However, note that the interference avoidance must be two-way, that is, one must not only avoid interference from the macro cell to home-eNodeB devices in the high-interference outer region of the home-eNodeB coverage area, but also home-eNodeB interference to devices close to the home-eNodeB but not being part of the home-eNodeB CSG. Furthermore, most interference coordination scheme assumes the presence of an X2 interface between the macro and home eNodeB, which may not always hold. Therefore, if closed subscriber groups are supported, it is preferable to use a separate carrier for the CSG cells to maintain the overall performance of the radio-access network. Interference handling between CSG cells, which typically lack backhaul-based coordination schemes, could rely on distributed algorithms for power control and/or resource partitioning between the cells.