CHAPTER

SMALL-CELL ENHANCEMENTS AND DYNAMIC TDD 15

Low-power nodes, or small cells, have attracted a lot of interest, the reason being the need for a dense deployment in order to provide very high data rates and high capacity. LTE is already from its first release capable of providing high performance in a wide range of scenarios, including both wide-area and local-area access. However, with most users being stationary or slowly moving, there is an increasing focus on high data rates in (quasi-)stationary situations. A number of features have been introduced to the LTE standard aiming at improving the support for low-power nodes in release 12. In this chapter, two of these features, namely small-cell on/off and dynamic TDD, are described. Before describing these features, note that there are also other features, not described in this chapter but related to small-cell improvements. Chapter 14 discusses how low-power nodes can be deployed together with macro nodes, resulting in a so-called heterogeneous deployment. Dual connectivity, described in Chapter 16, was developed in 3GPP under the umbrella of small-cell enhancements, as was the extension to 256QAM described in Chapter 6. Interworking with 802.11-based WLAN and license-assisted access, see Chapter 17, are other examples of features mainly relevant in a deployment with low-power nodes.

15.1 SMALL-CELL ON/OFF

In LTE, cells are continuously transmitting cell-specific reference signals and broadcasting system information, regardless of the traffic activity in the cell. One reason for this is to enable idle-mode devices to detect the presence of a cell; if there were no transmissions from a cell there is nothing for the device to measure upon and the cell would therefore not be detected. Furthermore, in a large macro-cell deployment there is a relatively high likelihood of at least one device being active in a cell, motivating continuous transmission of reference signals. LTE was designed with universal frequency reuse in mind and can handle the inter-cell interference from these transmissions.

However, in a dense deployment with a large number of relatively small cells, the likelihood of not all cells serving device at the same time can sometimes be relatively high. The downlink interference scenario experienced by a device may also be more severe with devices experiencing very low signal-to-interference ratios due to interference from neighboring, potentially empty, cells, especially if there is a large amount of line-of-sight propagation. In

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such dense, small-cell scenarios, selectively turning off cells can provide significant gains in reduced interference and reduced power consumption. The faster a cell is turned on or off, the more efficiently it can follow the traffic dynamics and the larger the gains are.

In principle, turning off a cell is straightforward and can be handled using existing network management mechanisms. However, even if there are no devices in a particular cell, turning off that cell has an impact on idle mode devices. In order not to impact these devices, other cells must provide basic coverage in the area otherwise handled by the cell turned off. Furthermore, the idle mode procedures in LTE are not designed under the assumption of cells being turned on or off frequently and it may take quite some time before a device discovers a cell that has been turned on. Transition from a dormant state to a fully active state for a cell takes many hundreds of milliseconds which is too slow to track any dynamic traffic variations and would have a noticeable performance impact.

With this as a background, mechanisms for significantly more rapid on/off operation of small cells[1] in a dense deployment, including on/off on a subframe level, were extensively discussed during the development of release 12. Based on these discussions, it was decided to base the release 12 small-cell on/off mechanism on the activation/deactivation mechanism in the carrier aggregation framework (see Chapter 12). This means that on/off is restricted to secondary cells in active mode only—that is, the primary carrier is always on. Restricting the on/off operation to secondary carriers greatly simplifies the overall design as idle mode compatibility is not impacted while the secondary carriers can be activated/deactivated on a fast basis.

When a secondary component carrier is turned off, a device should in principle not expect any transmissions on that carrier. This means that the device should not expect any synchronization signals, cell-specific reference signals, CSI reference signals, or system information from a deactivated cell. Although a carrier being completely silent would lead to the best energy savings and the lowest interference, it would also imply that the device cannot maintain synchronization to that carrier or perform any measurements, for example, mobility-related measurements. Without any active-mode mobility handling there is a significant risk that a device may have left the coverage area of a secondary cell without the network being aware of it. Therefore, to address these aspects, a new form of reference signal, the *discovery reference signal*, was introduced in release 12. The discovery signal is transmitted with a low-duty cycle and used by the device to perform mobility measurements and to maintain synchronization. The discovery signal, although designed as part of the small-cell on/off work, is useful also without switching off cells. For example, it can be used to assist shared-cell operation, described in Chapter 14, or full-dimension MIMO, discussed in Chapter 10. An example of small-cell on/off is shown in Figure 15.1.

[1]Although the feature is referred to as "small cell on/off" and a small-cell deployment was assumed in the discussions, the feature is not restricted to small cells from a specification perspective.

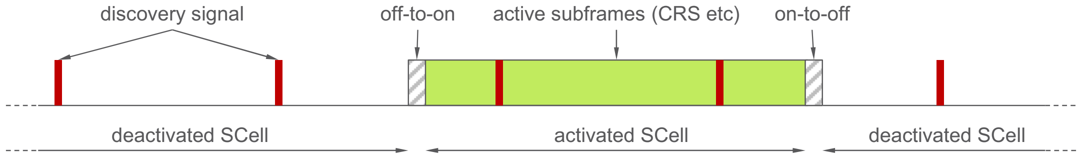

FIGURE 15.1

Small-cell on/off.

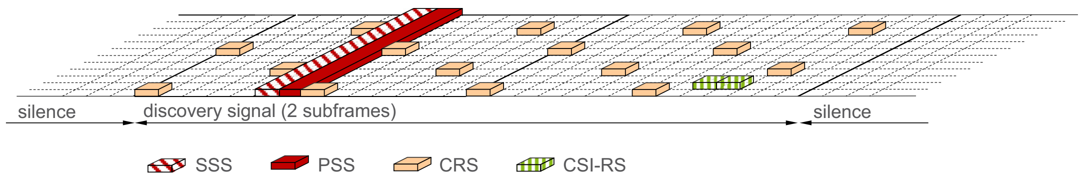

FIGURE 15.2

Example of discovery signal transmission for FDD.

15.1.1 DISCOVERY SIGNAL AND ASSOCIATED MEASUREMENTS

The *discovery reference signal* (DRS), although described as a new signal, actually consists of a combination already existing signals, namely

- synchronization signal (PSS and SSS) to assist in obtaining the cell identity and coarse frequency and time synchronization;
- cell-specific reference signals (CRS) to assist in obtaining fine frequency and time synchronization;
- CSI reference signals (optional) useful in determining the transmission point identity within the cell.

In the specifications, the discovery signal is defined from a device point of view. More specifically, a so-called *discovery signal occasion* is one to five subframes (two to five for TDD) where the device may assume the above-mentioned signals being present, starting with the synchronization signals in the first subframe.[2] This is illustrated in Figure 15.2. The periodicity of the DRS occasions can be set to 40, 80, or 160 ms.

A discovery signal occasion always starts in subframe 0 or 5. This follows directly from the definition of synchronization signals where the secondary synchronization signal is transmitted in subframe 0 and 5 in both FDD and TDD. The CSI-RS, which is an optional part of the DRS, can be transmitted on antenna port 15 in any of the subframes in the discovery

[2]For TDD the secondary synchronization signal is in the first subframe and the primary synchronization signal in the second subframe as a consequence of the synchronization signal design. This is also the reason behind the shortest possible discovery signal duration of two subframes in TDD.

signal occasion, subject to any restrictions in each of the subframes. The purpose of the CSI-RS is to be able to identify individual transmission points belonging to the same physical-layer cell identity. This can be used for selectively turning on certain transmission points in the cell in response to a device measurement report as discussed in conjunction with shared-cell operation in Chapter 14. As shown in Figure 15.2 there are several possible locations for a CSI-RS in a subframe. In FDD, there are up to 96 different positions, assuming a five subframes long discovery signal occasion starting in subframe 5,[3] thus allowing a large number of transmission points to be identified. The different CSI-RS locations can also be used to create orthogonality between transmission points by, on a given resource element, transmit nonzero-power CSI-RS from one transmission point and zero-power CSI-RS from the others.

Radio-resource management can be based on DRS—that is, the device need to base cell identification and radio-resource management measurements such as *reference signal received power* (RSRP) and *reference signal received quality* (RSRQ) on the DRS instead of the PSS/SSS/CRS mentioned in Chapter 11. The device is configured whether to use DRS-based measurements or not through RRC signaling. To assist these measurements, the device is provided with a *DRS measurements timing configuration* (DMTC) which indicates a 6 ms window within which a DRS may occur. If the CSI-RS are part of the DRS, the network also provides the device with information on, for each physical-layer cell identity, which CSI-RS configurations to measure upon and the virtual cell identity used for generating the CSI-RS sequences (the sequences for PSS/SSS and CRS are tied to the physical-layer cell identity). Within the DMTC, the device will search for discovery signals. For each of the discovery signals found fulfilling the triggering condition the device will report the RSRP and/or RSRQ together with information for cell and transmission point identification.

15.2 DYNAMIC TDD AND EIMTA

In LTE, seven different uplink–downlink configurations are possible as described in Chapter 5 where each subframe is either an uplink subframe or a downlink subframe (the special subframe can, to a large extent, be seen as a downlink subframe in this context). This configuration is in practice static, which is a reasonable assumption in larger macro cells. However, with an increased interest in local-area deployments, TDD is expected to become more important compared to the situation for wide-area deployments to date. One reason is that unpaired spectrum allocations are more common at higher-frequency bands less suitable for wide-area coverage but usable for local-area coverage. Furthermore, some of the problematic interference scenarios in wide-area TDD networks are less pronounced in local-area deployments with lower-transmission power and below-rooftop antenna installations. To better handle the high traffic dynamics in a local-area scenario, where the number of devices

[3]In this case there are 16 different configurations in subframe 5 and 20 different configurations in each of the following subframes; $16 + 4 \cdot 20 = 96$.

transmitting to/receiving from a local-area access node can be very small, dynamic TDD is beneficial. In dynamic TDD, the network can dynamically use resources for either uplink or downlink transmissions to match the instantaneous traffic situation, which leads to an improvement of the end-user performance compared to the conventional static split of resources between uplink and downlink. The more isolated a cell is, the better the traffic dynamics can be exploited. To harvest these benefits, LTE release 12 includes support for dynamic TDD, or *enhanced interference mitigation and traffic adaptation* (eIMTA) as is the official name for this feature in 3GPP.

One simple approach to dynamic TDD would be to, from a device perspective, treat every subframe as a downlink subframe, including the monitoring for control signaling, unless there is an uplink transmission explicitly scheduled. However, for various reasons 3GPP has chosen a somewhat different approach where the uplink—downlink allocation is signaled at the beginning of each frame (or set of frames) to enable dynamically varying uplink—downlink usage.

15.2.1 BASIC PRINCIPLES OF EIMTA

With the introduction of eIMTA, the uplink—downlink configuration is not static but can vary on a frame-by-frame basis. This is handled by the network broadcasting the *current uplink—downlink configuration* to use for each frame (or set of frames as discussed later).

The broadcasting allows the uplink—downlink configuration to change and meet different requirements on uplink and downlink traffic. However, there is also a need to handle uplink feedback such as hybrid-ARQ acknowledgments in response to downlink traffic, as well as uplink-related downlink control signaling. Having some subframes that are guaranteed to be downlink or uplink, irrespective of the dynamic reconfiguration, is therefore beneficial. For example, hybrid-ARQ feedback resulting from downlink transmissions is preferably transmitted in subframes guaranteed to be uplink to avoid error cases. Random-access transmissions also need a subframe guaranteed to be in the uplink direction. Therefore, eIMTA is making use of three different types of uplink—downlink configurations:

- the *uplink reference configuration*,
- the *downlink reference configuration*,
- the *current uplink-downlink configuration*.

The first two of these quantities are semi-statically configured and, among other things, determine the timing for the hybrid-ARQ signaling while the last one determines the usage of subframes in the current frame and can be dynamically changed on a frame-by-frame basis.

The *uplink reference configuration* is obtained from SIB1. It is also the configuration used by non-eIMTA-capable devices, simply known as the uplink—downlink configuration in earlier release. Preferably, to allow for the maximum flexibility for eIMTA-capable devices, this configuration is uplink heavy, hence its name. Downlink subframes in this reference configuration are guaranteed to be downlink subframes despite any dynamic reconfiguration

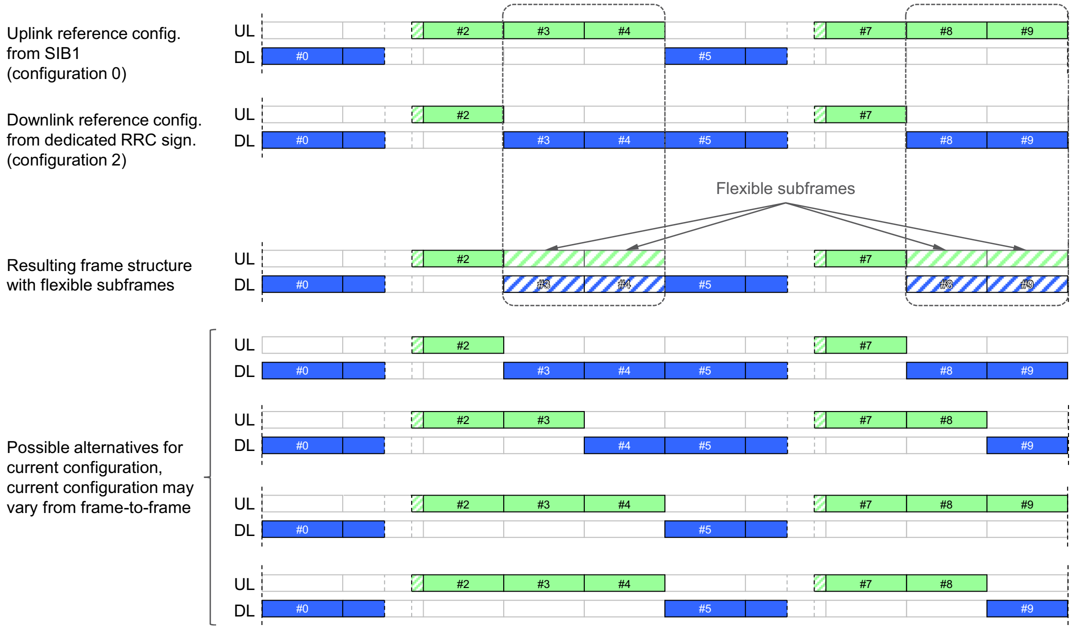

FIGURE 15.3

Example of flexible subframes.

and therefore useful for downlink transmission of, for example, the PHICH. In Figure 15.3, configuration 0 has been used as an example.

The *downlink reference configuration* is obtained from dedicated RRC signaling, specific to eIMTA-capable devices. As suggested by the name a downlink-heavy configuration is a good choice for maximum flexibility. A key property of this reference configuration is that uplink subframes are guaranteed to be uplink subframes despite any dynamic reconfiguration and therefore useful for hybrid-ARQ feedback as is discussed later. In Figure 15.3, configuration 2 has been used as an example for the downlink reference configuration. From the two reference configurations an eIMTA-capable device can compute the so-called *flexible subframes* as the difference between the two reference configurations. A flexible subframe can be used in either transmission direction as is described in the following.

The *current uplink–downlink configuration* determines which subframes that are uplink and which that are downlink in the current frame.[4] It must be chosen among the seven possible uplink–downlink allocations described in Chapter 5 and be within the limits set by the flexible subframes obtained from the reference configurations. This is the configuration that is broadcasted regularly and can be dynamically changed in order to follow traffic

[4]In case the uplink reference configuration and the current subframe configuration indicating a certain subframe as special and downlink subframe, respectively, the subframe is a downlink subframe.

variations. In Figure 15.3, the four different possibilities for the current uplink−downlink configuration in the example are illustrated.

The current uplink−downlink allocation is broadcasted using DCI format 1C on the PDCCH to all eIMTA-enabled devices. A special identity, the eIMTA-RNTI, is used on the control channel to indicate the current configuration. Multiple three-bit fields are used in DCI format 1C, each field indicating one of the seven uplink−downlink configurations in Chapter 5 for each of the component carriers the device is configured with, subject to any restrictions arising from the reference configurations.

From the perspective of dynamically adapting to varying traffic conditions, it is beneficial to broadcast the current configuration as often as possible—that is for each frame. From a signaling overhead perspective, on the other hand, less-frequent signaling results in a lower overhead. Therefore, the signaling periodicity for the current configuration can be set to once per 10, 20, 40, or 80 ms. It is also possible to configure in which of the subframes the device will monitor for the DCI format 1C carrying the current subframe allocation.

Upon detecting the DCI format 1C using the eIMTA-RNTI, the device will set the current uplink−downlink configuration accordingly. However, a device may occasionally not succeed in receiving the current uplink−downlink allocation and thus may not know which subframes that are uplink and which that are downlink. Therefore, a device not detecting the current uplink−downlink configuration will assume the current allocation being equal to the uplink reference configuration for the coming frame(s). In other words, the device behaves in the same way as a non-eIMTA-enabled device in this situation.

Figure 15.4 illustrates an example of eIMTA operation with the same reference configurations as in Figure 15.3. The current uplink−downlink configuration is broadcasted to all

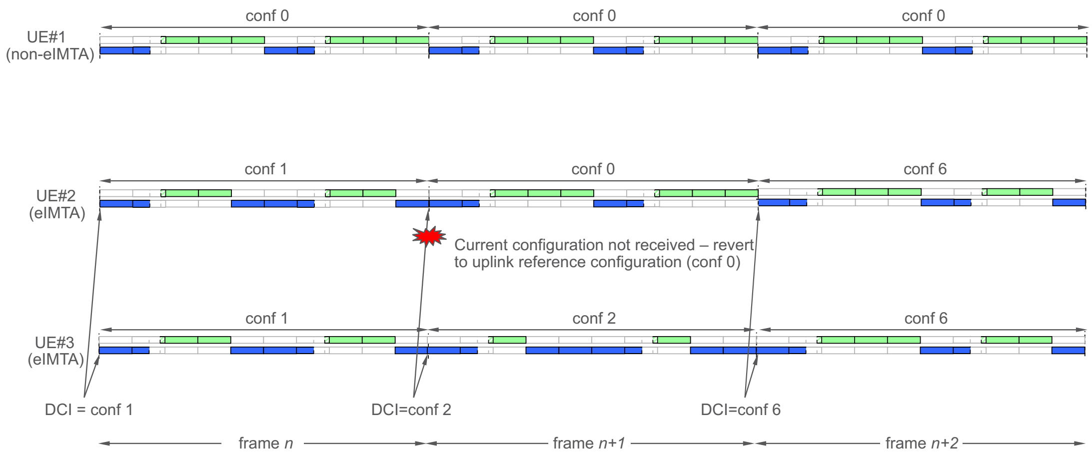

FIGURE 15.4

Example of eIMTA operation.

eIMTA-enabled devices one per frame. In frames n and $n+2$ both devices received the current configuration correctly and applied the corresponding uplink–downlink configuration. In frame $n+1$, however, the first device did not receive the current configuration. Hence, as a fallback, it applied the uplink reference configuration for that frame.

15.2.2 SCHEDULING AND HYBRID-ARQ RETRANSMISSIONS

The basic principle described earlier, to dynamically configure the uplink–downlink allocation for each frame, works nicely from a downlink scheduling perspective. The eNodeB can, using any downlink subframe in the current configuration, schedule downlink data. In response to the downlink data transmission, hybrid-ARQ acknowledgments need to be transmitted from the device in an uplink subframes. The timing of those acknowledgments is given by the downlink reference configuration in a similar way as for carrier aggregation with different uplink–downlink configurations—that is, they are transmitted in subframes guaranteed to be uplink subframes. Restricting hybrid-ARQ feedback to guaranteed uplink subframes instead of using "any" uplink subframe is beneficial as it maintains a fixed timing also in case the device has not properly received the configuration for the current frame. Improper reception of the current configuration is also the reason why bundling of hybrid-ARQ acknowledgments is not supported in eIMTA. Furthermore, the downlink reference configuration is used to derive the number of hybrid-ARQ processes.

Uplink scheduling is somewhat more complicated as the uplink grant received in one downlink subframe controls uplink transmission in a later subframe, the timing of which is given by the specifications. To be able to reuse the already developed timing relations—that is, which downlink subframe to use to schedule uplink transmission in a certain subframe—uplink grants are restricted to be transmitted in the guaranteed downlink subframes only. Similarly, the PHICH, which essentially is an uplink retransmission grant, follows the same principle. Obviously, if the scheduler has scheduled an uplink (re)transmission in a certain (flexible) subframe, that subframe cannot be used for downlink transmission.

From the discussion on the downlink and uplink reference configurations in the previous section, a relevant question is why these configurations, at least the downlink reference configuration which is of no relevance for legacy devices, are configurable. One alternative solution would be to hard code the downlink reference configuration to configuration 5, the most downlink-heavy configuration. The answer lies in the hybrid-ARQ latency and the fact that a downlink-heavy configuration results in fewer subframes available for hybrid-ARQ feedback and consequently a larger delay for hybrid-ARQ feedback. With configurable reference configurations, it is possible to balance the hybrid-ARQ latency against the number flexibility in subframe allocation.

15.2.3 RRM MEASUREMENTS AND CSI REPORTING

In a dynamic TDD network, the transmission direction of subframes is not necessarily aligned across multiple cells. Consequently, the interference scenario may be substantially different between subframes guaranteed to be downlink and subframes that are flexibly assigned to downlink. This will impact not only measurements for radio-resource management, for example, handover decisions, but also rate control.

Handover decisions should be consistent and not be influenced by short-term traffic variations. Therefore, measurements such as RSRP and RSRQ used for mobility handling are made upon guaranteed downlink subframes and not impacted by changes in the current uplink—downlink configuration. The mobility and handover behavior of an eIMTA-enabled device and a (legacy) device following the semi-statically signaled configuration (the uplink reference) is therefore identical.

Rate control, on the other hand, should reflect the instantaneous channel conditions at the device. Since the interference behavior can be quite different between guaranteed and flexible downlink subframes, interference is measured separately for the two sets of subframes and CSI reports provided separately for each of the two sets.

15.2.4 UPLINK POWER CONTROL

Uplink interference can, similarly to the downlink case, be radically different in subframes guaranteed to be uplink and subframes dynamically assigned for uplink transmissions. Different transmission power setting can therefore be useful, allowing the uplink transmission power to be set to a higher value to counteract interference from simultaneous downlink transmissions in neighboring cells in case of uplink subframes flexibly assigned compared to guaranteed uplink subframes.

In eIMTA, this is handled through independent power control loops: one for dynamically assigned uplink subframes and one for guaranteed uplink subframes. For each of the two sets of subframes, power control is handled as described in Chapter 7 with the parameters separately configured for each of the two subframe sets.

15.2.5 INTER-CELL INTERFERENCE COORDINATION

Dynamic TDD allows the uplink—downlink configuration to change dynamically on a per-cell basis. Although one of the reasons for dynamic TDD is to follow rapid changes in traffic behavior in a cell, it may not always be feasible to dynamically adapt the uplink—downlink configuration without coordination with neighboring cells. In an isolated cell, completely independent adaptation is possible, while in a large macro network a more or less static allocation as LTE was originally designed for may be the only possibility. However, there is a large range of scenarios between these two extremes were a dynamic TDD is possible with some degree of inter-cell coordination.

Between cells belonging to the same eNodeB this is purely as implementation issue in the scheduling algorithm. However, when the cells to coordinate between belong to different eNodeBs, coordination across the X2 interface is required. To assist interference coordination across cells in eIMTA, a new X2 message, the *intended uplink—downlink configuration* is introduced, and the *overload indicator* part of the release 8 inter-cell interference coordination framework (ICIC, see Chapter 13) is extended.

The intended uplink–downlink configuration is an X2 message where one cell can indicate the uplink–downlink configuration it intends to use for the coming period to neighboring cells. The scheduler in the cell receiving this massage can take this into account when determining the configuration to use in that cell. For example, if the neighboring cell indicates a flexible subframe will be used for uplink transmission, the cell receiving this message may try to avoid assigning the same flexible subframe for downlink transmissions.

The *overload indicator* in ICIC, indicates the uplink interference experienced by a cell on its different resource blocks. For TDD, the overload indicator refers to the uplink reference configuration—that is, the uplink–downlink configuration used by non-eIMTA devices. With the introduction of eIMTA, an extended overload indicator is added. The extended overload indicator is identical to the release 8 overload indicator with the addition of information about which uplink subframes it relates to, thus allowing interference information related to the current uplink–downlink configuration.