CHAPTER

CARRIER AGGREGATION

12

The possibility for *carrier aggregation* (CA) was introduced in LTE release 10 with enhancements in the following releases. In the case of carrier aggregation, multiple LTE carriers, possibly of different bandwidths up to 20 MHz, can be transmitted in parallel to/from the same device, thereby allowing for an overall wider bandwidth and correspondingly higher per-link data rates. In the context of carrier aggregation, each carrier is referred to as a *component carrier*[1] as, from a radio-frequency (RF) point of view, the entire set of aggregated carriers can be seen as a single (RF) carrier.

Initially, up to five component carriers could be aggregated allowing for overall transmission bandwidths up to 100 MHz. In release 13 this was extended to 32 carriers allowing for an overall transmission bandwidth of 640 MHz, primarily motivated by the possibility for large bandwidths in unlicensed spectrum. A device capable of carrier aggregation may receive or transmit simultaneously on multiple component carriers. Each component carrier can also be accessed by an LTE device from earlier releases, that is, component carriers are *backward compatible*. Thus, in most respects and unless otherwise mentioned, the physical-layer description in the previous chapters applies to each component carrier separately in the case of carrier aggregation.

It should be noted that aggregated component carriers do not need to be contiguous in the frequency domain. Rather, with respect to the frequency location of the different component carriers, three different cases can be identified (see also Figure 12.1):

- Intraband aggregation with frequency-contiguous component carriers.
- Intraband aggregation with noncontiguous component carriers.
- Interband aggregation with noncontiguous component carriers.

The possibility to aggregate nonadjacent component carriers allows for exploitation of a fragmented spectrum; operators with a fragmented spectrum can provide high-data-rate services based on the availability of a wide overall bandwidth, even though they do not possess a single wideband spectrum allocation. Except from an RF point of view there is no difference between the three different cases outlined in Figure 12.1 and they are all supported

[1] In the specifications, the term "cell" is used instead of component carrier, but as the term "cell" is something of a misnomer in the uplink case, the term "component carrier" is used here.

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00012-1

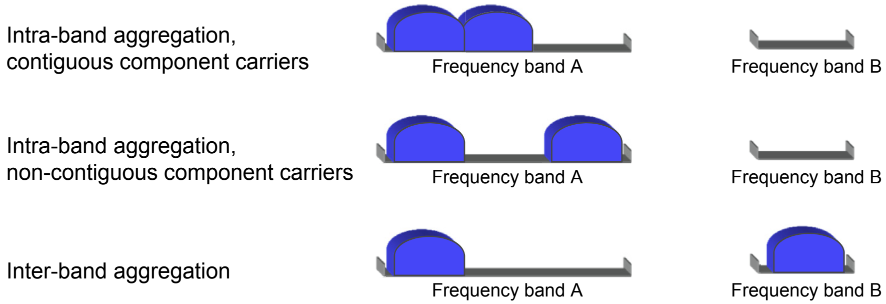

FIGURE 12.1

Different types of carrier aggregation.

by the LTE release10 specification. However, the complexity of RF implementation is vastly different as discussed in Chapter 22, with the first case being the least complex. Thus, although spectrum aggregation is supported by the physical-layer and protocol specifications, the actual implementation will be strongly constrained, including specification of only a limited number of aggregation scenarios and aggregation over a dispersed spectrum only being supported by the most advanced devices.

Although carrier aggregation can be utilized to achieve very high overall bandwidths, up to 100 MHz or even 640 MHz, very few operators, if any, have such large spectrum allocations. Rather, the main usage of carrier aggregation, at least initially, was to handle fragmented spectrum allocations in which an operator may have 5−10 MHz of spectrum allocation in several bands and, despite this, would like to provide end-user performance on par with an operator having a larger amount of contiguous spectrum.

In releases 10 and 11, only downlink-heavy asymmetries are supported from an RF perspective; that is, the number of uplink component carriers configured for a device is always equal to or smaller than the number of configured downlink component carriers. Uplink-heavy asymmetries are less likely to be of practical interest and would also complicate the overall control signaling structure, as in such a case multiple uplink component carriers would need to be associated with the same downlink component carrier.

Carrier aggregation is supported for all frame structures. In release 10, all aggregated component carriers need to have the same duplex scheme and, in case of TDD, the same uplink−downlink configuration across the component carriers.

For carrier aggregation capable TDD devices in release 11, different uplink−downlink configurations can be used for component carrier in *different* frequency band. The main motivation is improved support for coexistence with other systems. One example is two independent legacy systems operating in two different frequency bands. Clearly, if LTE is to exploit spectrum in both of these bands through carrier aggregation, the uplink−downlink allocation of the component carriers in the respective band is basically determined by the legacy systems and may very well be different.

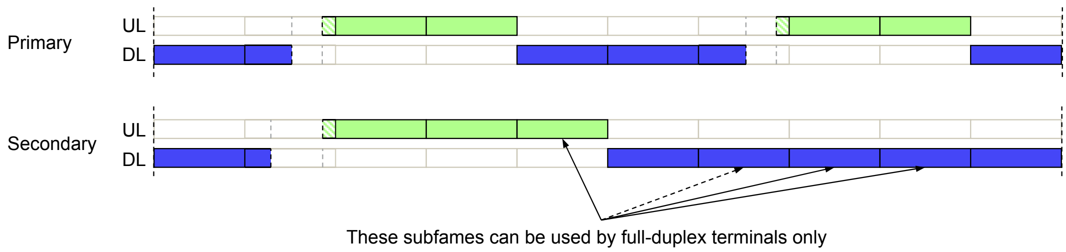

FIGURE 12.2

Examples of TDD interband CA with different uplink—downlink configurations.

It is worth noting that interband carrier aggregation with *different* uplink—downlink configurations may imply *simultaneous* uplink transmission and downlink reception in the device. Devices capable of simultaneous transmission and reception need, similarly to FDD devices and unlike most TDD devices, a duplex filter. Whether a TDD device is equipped with a duplex filter and capable of simultaneous transmission and reception is therefore a matter of device capability. Devices not having this capability follow the uplink—downlink configuration on one of the component carriers, the primary carrier (primary and secondary component carriers are described in the next section). These devices cannot transmit in the uplink on a secondary component carrier whenever there is a downlink subframe on the primary component carrier (and vice versa). In essence this implies certain subframes on some of the carriers being unusable by devices not capable of simultaneous reception and transmission, see Figure 12.2.[2]

The special subframe configuration can be different for the different components carriers although devices not capable of simultaneous transmission and reception require that the resulting downlink—uplink switch time is sufficiently large.

In release 12, carrier aggregation was further enhanced by allowing aggregation between FDD and TDD to enable efficient utilization of an operator's overall spectrum assets. The primary component carrier can use either FDD or TDD. Aggregation across the duplex schemes can also be used to improve the uplink coverage of TDD by relying on the possibility for continuous uplink transmission on the FDD carrier.

Release 13 increased the number of carriers possible to aggregate from 5 to 32, resulting in a maximum bandwidth of 640 MHz and a corresponding theoretical peak data rate of approximately 25 Gbit/s in the downlink. The main motivation for increasing the number of subcarriers is to allow for very large bandwidths in unlicensed spectrum as is further discussed in conjunction with license-assisted access later.

The evolution of carrier aggregation across different releases is illustrated in Figure 12.3.

[2]The downlink subframe on the secondary component carrier overlapping with the special subframe on the primary component carrier can only be used in the part overlapping with the DwPTS.

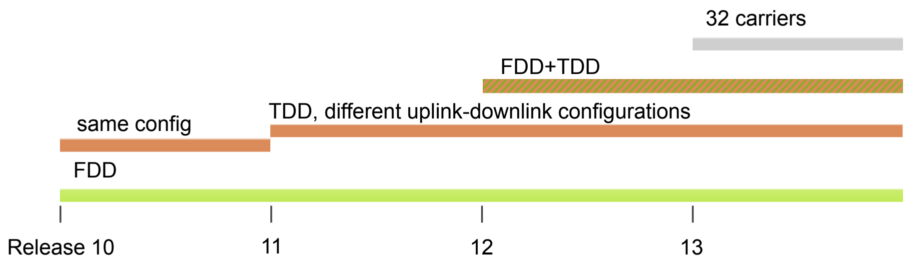

FIGURE 12.3

Evolution of carrier aggregation.

12.1 OVERALL PROTOCOL STRUCTURE

Carrier aggregation is essentially duplicating the MAC and PHY processing for each component carrier while keeping radio-link control (RLC) and above identical to the non-aggregation case (Figure 12.4). Hence, one RLC entity may handle data transmitted across multiple component carriers in the presence of carrier aggregation. The MAC entity is responsible for distributing data from each flow across the component carriers, a decision that is part of the implementation-specific scheduling approach in the downlink. Each component carrier has its own hybrid-ARQ entity, implying that hybrid-ARQ retransmissions must occur on the same component carrier as the original transmission. There is no possibility to move hybrid-ARQ retransmissions between carriers. RLC retransmissions, on the other hand, are not tied to a specific component carrier as, in essence, CA is invisible above the MAC layer. RLC retransmissions can therefore use a different component carrier than the original transmission. The RLC also handles reordering across component carriers to ensure in-sequence in

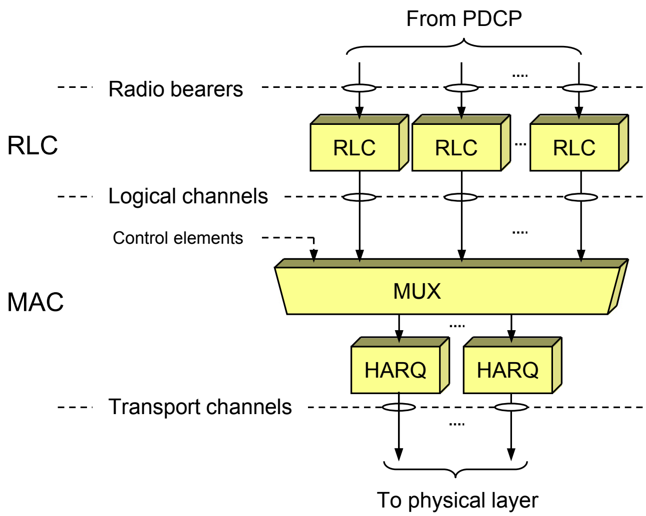

FIGURE 12.4

RLC and hybrid-ARQ retransmission mechanisms in LTE.

case a radio bearer is transmitted on multiple component carriers. Since hybrid-ARQ retransmissions are handled independently per component carrier, out-of-sequence delivery from the MAC layer may occur not only on one component carrier as described in Chapter 8 but also between component carriers.

Each component carrier is independently scheduled with individual scheduling assignments/grants per component carrier in case of carrier aggregation. The scheduling assignment/grant can either be transmitted on the same carrier as data (self-scheduling) or on another component carrier (cross-carrier scheduling) as is described in more detail in Section 12.3.

12.2 PRIMARY AND SECONDARY COMPONENT CARRIERS

A device capable of carrier aggregation has one downlink primary component carrier and an associated uplink primary component carrier. In addition, it may have one or several secondary component carriers in each direction. Different devices may have different carriers as their primary component carrier—that is, the configuration of the primary component carrier—is device specific. The association between the downlink primary carrier and the corresponding uplink primary carrier is signaled as part of the system information. This is similar to the case without carrier aggregation, although in the latter case the association is trivial. The reason for such an association is, for example, to determine to which uplink component carrier a certain scheduling grant transmitted on the downlink relates without having to explicitly signal the component-carrier number. In the uplink, the primary carrier is of particular interest as it, in many cases, carries all the L1/L2 uplink control signaling as described later in this chapter.

All idle mode procedures apply to the primary component carrier only or, expressed differently, carrier aggregation with additional secondary carriers configured only applies to devices in the RRC_CONNECTED state. Upon connection to the network, the device performs the related procedures such as cell search and random access (see Chapter 11 for a detailed description of these procedures) following the same steps as in the absence of carrier aggregation. Once the communication between the network and the device is established, additional secondary component carriers can be configured.

The fact that carrier aggregation is device specific—that is, different devices may be configured to use different sets of component carriers—is useful not only from a network perspective to balance the load across component carriers, but also to handle different capabilities between devices. Some devices may be able to transmit/receive on multiple component carriers, while other devices may do so on only a single carrier. This is a consequence of being able to serve devices from earlier releases at the same time as a carrier aggregation-capable device, but it also allows for different capabilities in terms of carrier aggregation for different devices as well as a differentiation between downlink and uplink carrier aggregation capability. For example, a device may be capable of two component carriers in the downlink but of only a single component carrier—that is, no carrier aggregation—in the uplink, as is the case for device C in Figure 12.5. Note also that the primary component-carrier configuration can differ between devices. Asymmetric carrier aggregation can also be useful to handle different spectrum allocations, for example if an

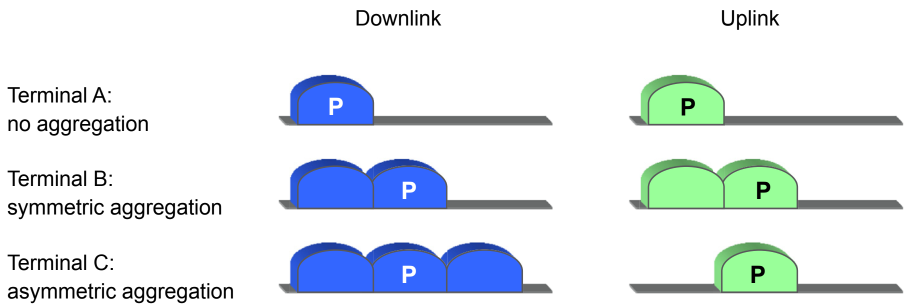

FIGURE 12.5

Examples of carrier aggregation ("P" denotes the primary component carrier).

operator has more spectrum available for downlink transmissions than uplink transmissions. Semipersistent scheduling is only supported on the primary component carrier, motivated by the fact that the main usage is for small payloads not requiring multiple component carriers.

12.3 SELF-SCHEDULING AND CROSS-CARRIER SCHEDULING

Each component carrier is, as already mentioned, individually scheduled with the scheduling assignment/grant transmitted on either the same (associated) component carrier as the data (self-scheduling) or on a different component carrier than the data (cross-carrier scheduling). The two possibilities are illustrated in Figure 12.6.

For self-scheduling, downlink scheduling assignments are valid for the component carrier upon which they are transmitted. Similarly, for uplink grants, there is an association between downlink and uplink component carriers such that each uplink component carrier has an associated downlink component carrier. The association is provided as part of the system information. Thus, from the uplink–downlink association, the device will know to which uplink component carrier the downlink control information relates to.

For cross-carrier scheduling, where downlink PDSCH or uplink PUSCH is transmitted on an (associated) component carrier other than that which (E)PDCCH is transmitted upon, the

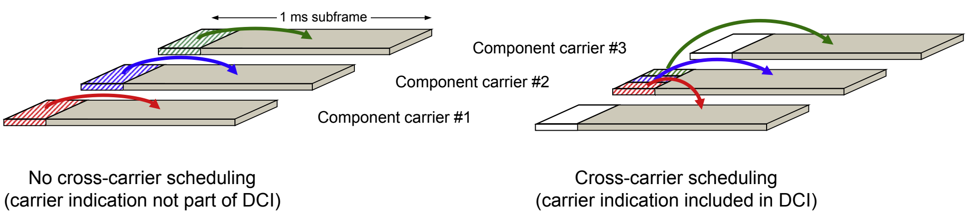

FIGURE 12.6

Self-scheduling (left) and cross-carrier scheduling (right).

carrier indicator in the PDCCH provides information about the component carrier used for the PDSCH or PUSCH.

Whether cross-carrier scheduling is used or not is configured using higher-layer signaling. Irrespective of whether self-scheduling or cross-carrier scheduling is used the hybrid-ARQ feedback is sent on the primary uplink carrier.[3] This structure was chosen to handle asymmetric carrier aggregation with more downlink carriers than uplink carriers, a common scenario. Two questions related to timing across the component carriers arise as a result of this structure, namely

- in which uplink subframe on the primary component carrier should the hybrid-ARQ acknowledgment related to data transmission in subframe n on a secondary component carrier be transmitted, and
- to which subframe does a scheduling grant received in subframe n relate to?

These timing relations are relatively straight forward for FDD but more complicated for TDD, in particular, in case of cross-carrier scheduling. The different timing scenarios are discussed in the following sections.

12.3.1 SCHEDULING TIMING FOR AGGREGATION OF FDD CARRIERS

The baseline for aggregation of multiple FDD component carriers is to follow the same timing relations for scheduling and retransmissions as in absence of carrier aggregation, that is, downlink scheduling assignments and the associated data are both transmitted in subframe n and the resulting acknowledgments in uplink subframe $n+4$. Note that, depending on the number of component carriers scheduled, there may be a relatively large number of acknowledgment bits transmitted in a single subframe. Similarly, uplink scheduling grants received in subframe n result in data transmission in subframe $n+4$ and PHICH being monitored in subframe $n+8$. Multiple PHICHs are used with each PHICH being transmitted on the same component carrier as the grant initiating the uplink data transmission. These timing relations hold for both self-scheduling and cross-carrier scheduling.

12.3.2 SCHEDULING TIMING FOR AGGREGATION OF TDD CARRIERS

In case of self-scheduling, timing of scheduling assignments and grants, including the PHICH, is straight forward and the same timing relations as in absence of carrier aggregation is used. Downlink scheduling assignments are transmitted on the same carrier as the corresponding data. Uplink data transmissions occur on the uplink component carrier associated with the downlink carrier used for transmission of the scheduling grant.

Downlink transmissions imply that the device needs to respond with hybrid-ARQ acknowledgments on the PUCCH (or PUSCH) on the primary component carrier. Obviously, an

[3]With aggregation of up to 32 carriers in release 13 this is extended to two uplink carriers, see further Section 12.6.

acknowledgment can only be transmitted in an uplink subframe on the primary component. In case of identical uplink–downlink allocations across all component carriers, the timing of the acknowledgments is the same as in absence of CA. However, release 11 introduced the possibility of having *different* allocations on different component carriers and release 12 introduced the possibility to aggregate FDD and TDD carriers, which complicates the timing relations further in case of TDD on the primary component carrier. If the timing of the hybrid-ARQ acknowledgment would follow the primary component carrier only, there would be no timing relation for the secondary component carrier in some subframes (subframe 4 in Figure 12.7) and, consequently, it would not be possible to use those subframes for downlink data transmissions. Therefore, to handle this case, a reference configuration, compatible with the hybrid-ARQ timing of both the primary component carrier and all secondary component carriers is used to derive the hybrid-ARQ timing relations for the secondary component carriers. The primary component carrier uses the same timing as in the absence of CA. See Figure 12.7 for an example of aggregation of primary and secondary component carriers using configurations 3 and 1, respectively, in which case configuration 4 is used as a reference for the timing of any secondary component carrier. The reference configuration for other combinations of configurations can be found in Table 12.1.

For cross-carrier scheduling, the timing of not only the hybrid-ARQ acknowledgments but also the scheduling grants and scheduling assignments can become quite involved. In case of the same uplink–downlink configuration across all component carriers, the scheduling timing is similar to that of self-scheduling as there is no timing conflict across the component carriers. However, cross-carrier scheduling with different uplink–downlink allocations requires special attention as the downlink scheduling timing for each component carrier follows that of the primary component carrier. Together with the fact that a scheduling assignment cannot point to a downlink subframe in the future, this implies that some downlink subframes on some component carriers cannot be scheduled with cross-carrier scheduling, see Figure 12.8. This is consistent with the fact that, for a TDD device not capable of simultaneous transmission and reception, only downlink (uplink) subframe on a secondary component carrier that coincides with a downlink (uplink) subframe on the primary component carrier may be used. Note though that in absence of cross-carrier scheduling all subframes can be scheduled.

Uplink scheduling timing in presence of cross-carrier scheduling is rather complex. For some configurations the timing is given by the configuration of the scheduling carrier—the carrier on which the (E)PDCCH is transmitted—while for other configurations, the timing follows the configuration of the scheduled carrier, that is, the carrier upon which the PUSCH was transmitted. The same relations hold for PHICH as well, as it in essence is a single-bit uplink grant.

In case of cross-carrier scheduling, no reference configuration is needed for hybrid-ARQ acknowledgments in response to downlink transmissions as the scheduling timing for each component carrier follows the primary component. The "problematic" subframe, subframe 4 in Figure 12.7, can therefore never be scheduled and the hybrid-ARQ timing relations can be

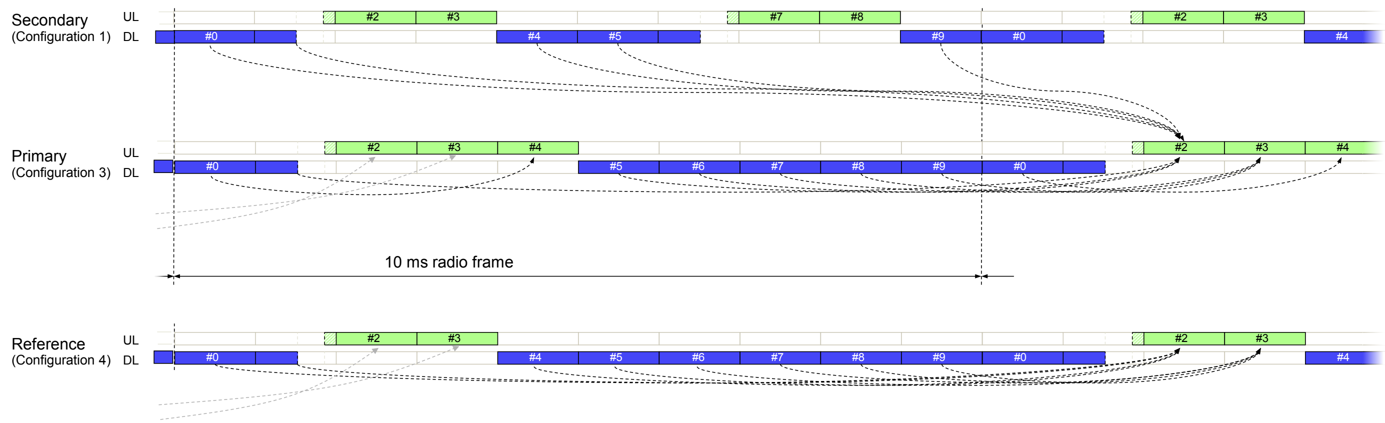

FIGURE 12.7

Aggregation of a primary component carrier with configuration 3 and a secondary component carrier with configuration 1.

Table 12.1 Uplink–Downlink Reference Configuration for Different Configurations on Primary and Secondary Component Carriers

		Secondary Component Carrier						
		0	**1**	**2**	**3**	**4**	**5**	**6**
Primary component carrier	**0**	0	1	2	3	4	5	6
	1	1	1	2	4	4	5	1
	2	2	2	2	5	5	5	2
	3	3	4	5	3	4	5	3
	4	4	4	5	4	4	5	4
	5	5	5	5	5	5	5	5
	6	6	1	2	3	4	5	6

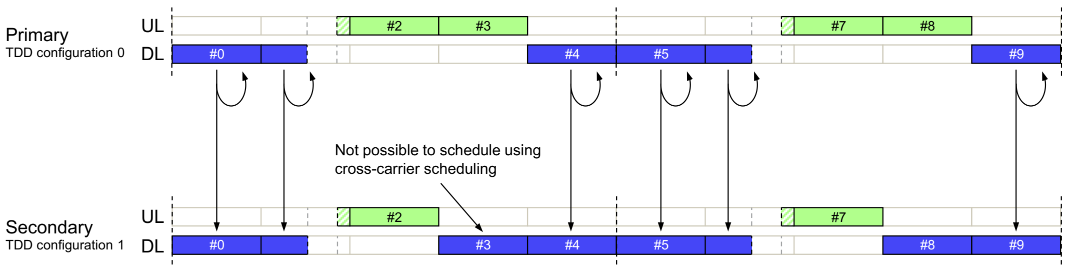

FIGURE 12.8

Example of cross-carrier scheduling with different TDD configurations.

derived from the primary component carrier alone (or, expressed differently, the reference timing configuration is identical to the configuration of the primary component carrier).

12.3.3 SCHEDULING TIMING FOR AGGREGATION OF FDD AND TDD CARRIERS

Many of the timing aspects discussed earlier apply also for the case of aggregation of FDD and TDD carriers.

In case of aggregation of FDD and TDD component carriers with the primary component carrier using FDD, there is always an uplink subframe available and consequently hybrid-ARQ acknowledgments can be transmitted using the FDD timing. Scheduling assignments and grants, including the PHICH, follow the timing of the secondary component carrier. This is obviously needed for self-scheduling but is, for simplicity, also used for cross-carrier scheduling.

In case of aggregation of FDD and TDD component carriers with the primary component carrier using TDD, the timing of downlink assignment and uplink grants is straight forward and the FDD timing is reused, that is, an uplink scheduling grant received in subframe *n* implies uplink transmission in subframe $n + 4$. This holds for both self-scheduling and cross-carrier scheduling. Note that this implies that some subframes on the FDD component carriers cannot be scheduled from a TDD component carrier, similarly to the illustration in Figure 12.8.

However, the PHICH timing does not follow the FDD timing. Rather, the PHICH is transmitted six subframes after the uplink data being received. The reason for this, and not the normal FDD timing of $n + 4$, is to guarantee that there is a downlink subframe to transmit the PHICH in. Since $6 + 4 = 10$, the PHICH is transmitted one frame later than the uplink grant, which matches the periodicity of the uplink–downlink configuration. This is illustrated in Figure 12.9. The scheduling grant in subframe 0 triggers an uplink transmission in subframe 4 and a retransmission is requested using PHICH in the next subframe 0. In this example the FDD PHICH time would have worked as well (with a PHICH in subframe 8). However, for a grant in subframe 9, triggering an uplink transmission in subframe 3, the FDD PHICH time would not have worked as subframe 7 on the primary carrier is not a downlink subframe.

The timing of the hybrid-ARQ acknowledgment in the uplink in response to downlink data transmission is somewhat complex and is given by a table in the specifications, ensuring that the acknowledgment is transmitted in an uplink subframe on the primary component carrier. One example is given in Figure 12.10.

12.4 DRX AND COMPONENT-CARRIER DEACTIVATION

Discontinuous reception (DRX) was described in Section 9.7 as a means to reduce the device power consumption. This holds equally well for a device with CA and the same DRX mechanism is applied across all component carriers. Hence, if the device is in DRX it is not receiving on any component carrier, but when it wakes up, all (activated) component carriers will be woken up.

Although discontinuous reception greatly reduces the device power consumption, it is possible to go one step further in the case of carrier aggregation. From a power-consumption perspective, it is beneficial to receive on as few component carriers as possible. LTE therefore supports deactivation of downlink component carriers. A deactivated component carrier maintains the configuration provided by RRC but cannot be used for reception, neither PDCCH nor PDSCH. When the need arises, a downlink component carrier can be activated rapidly and used for reception within a few subframes. A typical use would be to configure several component carriers but deactivate all component carriers except the primary one. When a data burst starts, the network could activate several component carriers to maximize the downlink data rate. Once the data burst is delivered, the component carriers could be deactivated again to reduce device power consumption.

Activation and deactivation of downlink component carriers are done through MAC control elements. There is also a timer-based mechanism for deactivation such that a device may, after a configurable time with no activity on a certain component carrier, deactivate that

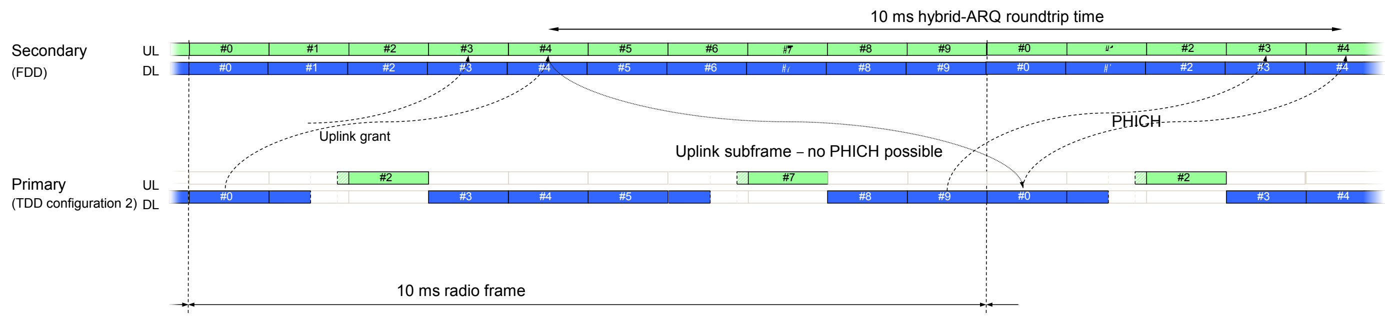

FIGURE 12.9

PHICH timing with the primary carrier using TDD.

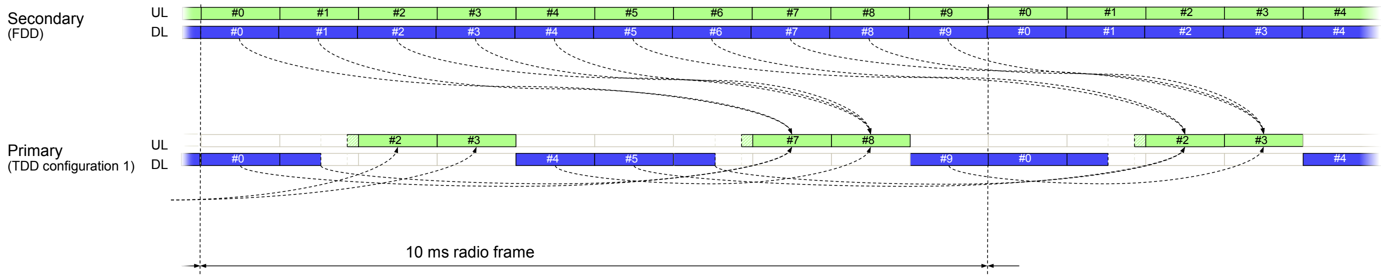

FIGURE 12.10

Example of hybrid-ARQ acknowledgment timing when aggregating FDD with TDD.

component carrier. The primary component carrier is always active as it must be possible for the network to communicate with the device.

In the uplink there is no explicit activation of uplink component carriers. However, whenever a downlink component carrier is activated or deactivated, the corresponding uplink component carrier is also activated or deactivated.

12.5 DOWNLINK CONTROL SIGNALING

Carrier aggregation uses the same set of L1/L2 control channels—PCFICH, (E)PDCCH, and PHICH—as in the nonaggregated case. However, there are some enhancements introduced, in particular to handle the larger number of hybrid-ARQ acknowledgments, as detailed in the following subsections.

12.5.1 PCFICH

The structure of each component carrier is the same as for the nonaggregated scenario, implying there is one PCFICH per component carrier. Independent signaling of the control-region size on the different component carriers is used, implying that the control region may be of different size on different component carriers. Hence, in principle the device needs to receive the PCFICH on each of the component carriers it is scheduled upon. Furthermore, as different component carriers may have different physical-layer cell identities, the location and scrambling may differ across component carriers.

If cross-carrier scheduling is used, that is, control signaling related to a certain PDSCH transmission is transmitted on a component carrier other than the PDSCH itself, the device needs to know the starting position for the data region on the carrier upon which the PDSCH is transmitted. Using the PCFICH on the component carrier carrying the PDSCH would be possible in principle, although it would increase the probability of incorrectly decoding the PDSCH since there are two PCFICH instances, one for the PDCCH decoding on one component carrier and one for PDSCH reception on the other component carrier. This would be problematic, especially since one use of cross-carrier scheduling is enhanced support of heterogeneous deployments (see Chapter 14), where some of the component carriers may be subject to strong interference. Therefore, for cross-carrier scheduled transmissions, the start of the data region is not obtained from the PCFICH on that component carrier, but is configured on a semi-static basis. The semi-statically configured value may differ from the value signaled on the PCFICH on the component carrier carrying the PDSCH transmission.

12.5.2 PHICH

The PHICH follows the same principles as for the nonaggregated case, see Chapter 6. This means that the PHICH resource to monitor is derived from the number of the first resource block upon which the corresponding uplink PUSCH transmission occurred in combination with the reference-signal phase rotation signaled as part of the uplink grant. As a general principle, LTE transmits the PHICH on the same component carrier that was used for the grant scheduling the corresponding uplink data transmission. Not only is this principle general in the sense that it can handle symmetric as well as asymmetric CA, it is also beneficial from a device power consumption perspective as the device only need monitor the component carriers it monitors for uplink scheduling grants (especially as the PDCCH may override the PHICH to support adaptive retransmissions, as discussed in Chapter 8).

For the case when no cross-carrier scheduling is used, that is, each uplink component carrier is scheduled on its corresponding downlink component carrier, different uplink component carriers will by definition have different PHICH resources. With cross-carrier scheduling, on the other hand, transmissions on multiple uplink component carriers may need to be acknowledged on a single downlink component carrier, as illustrated in Figure 12.11. Avoiding PHICH collisions in this case is up to the scheduler by ensuring that different reference-signal phase rotations or different resource-block starting positions are used for the different uplink component carriers. For semipersistent scheduling the reference-signal phase rotation is always set to zero, but since semipersistent scheduling is supported on the primary component carrier only, there is no risk of collisions between component carriers.

12.5.3 PDCCH AND EPDCCH

The (E)PDCCH carries downlink control information. For self-scheduling there are no major impacts to the (E)PDCCH processing as each component carrier in essence is independent, at least from a downlink control signaling perspective. However, if cross-carrier scheduling is configured by device-specific RRC signaling, the component carriers that a specific control message relates to must be indicated. This is the background to the carrier indication field mentioned in Chapter 6. Thus, most of the DCI formats come in two “flavors,” with and

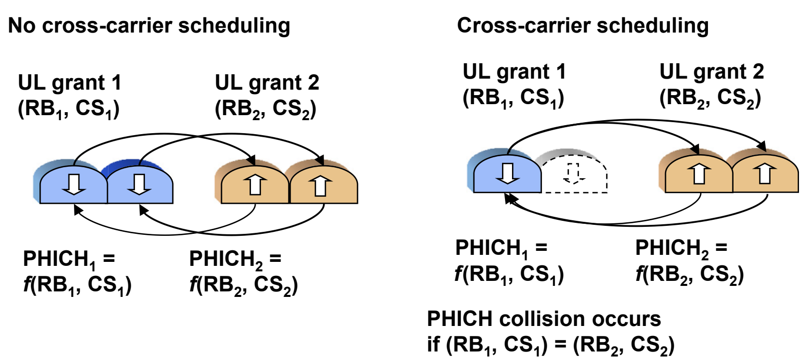

FIGURE 12.11

PHICH association.

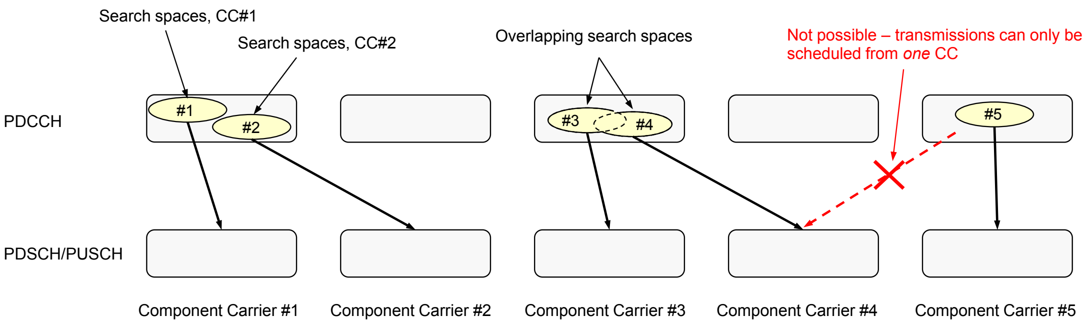

FIGURE 12.12

Example of scheduling of multiple component carriers.

without the carrier indication field, and which "flavor" the device is supposed to monitor is determined by enabling/disabling support for cross-carrier scheduling.

For signaling purposes, the component carriers are numbered. The primary component carrier is always given the number zero, while the different secondary component carriers are assigned a unique number each through device-specific RRC signaling. Hence, even if the device and the eNodeB have different understandings of the component-carrier numbering during a brief period of reconfiguration, at least transmissions on the primary component carrier can be scheduled.

Irrespective of whether cross-carrier scheduling is used or not, PDSCH/PUSCH on a component carrier can only be scheduled from *one* component carrier. Thus, for each PDSCH/PUSCH component carrier there is an associated component carrier, configured via device-specific RRC signaling, where the corresponding DCI can be transmitted. Figure 12.12 illustrates one example, where PDSCH/PUSCH transmissions on component carrier 1 are scheduled using PDCCHs/EPDCCHs transmitted on component carrier 1. In this case, as cross-carrier scheduling is not used, there is no carrier indicator in the corresponding DCI formats. PDSCH/PUSCH transmissions on component carrier 2 are cross-carrier scheduled from PDCCHs transmitted on component carrier 1. Hence, the DCI formats in the device-specific search space for component carrier 2 include the carrier indicator.

Note also that as transmissions on a component carrier can be scheduled by PDCCHs/EPDCCHs on *one* component carrier only, component carrier 4 cannot be scheduled by PDCCHs on component carrier 5 as the semi-static association between the component carriers used for PDCCH/EPDCCH transmission and the actual data transmission has associated data on component carrier 4, with PDCCHs/EPDCCHs on component carrier 3 in this example.

With respect to blind decoding and search spaces, the procedures described in Section 6.4.5 apply to each of the activated[4] downlink component carriers. Hence, in principle there is one device-specific search space per aggregation level and per (activated) component carrier

[4]Individual component carriers can be activated/deactivated as discussed in Section 12.4.

upon which PDSCH can be received (or PUSCH transmitted), although there are some carrier aggregation-specific modifications. For devices configured to use carrier aggregation, this results in an increase in the number of blind decoding attempts compared to a device not using carrier aggregation, as scheduling assignments/grants for each of the component carriers need to be monitored. With the up to 32 component carriers supported in release 13, the number of blind decodes could be 1036 (or even higher if uplink spatial multiplexing is used). From a processing capability perspective this is not a major issue for a high-end device (remember, 32 carriers correspond to peak data rates up to 25 Gbit/s) but it can be challenging from a power-consumption perspective. Therefore, release 13 introduced the possibility to configure the number of decoding candidates and to restrict the number of DCI formats per secondary component carriers (based on the number of blind decoding attempts the devices indicates it supports).

The common search space is only defined for transmissions on the primary component carrier. As the main function of the common search space is to handle scheduling of system information intended for multiple devices, and such information must be receivable by all devices in the cell, scheduling in this case uses the common search space. For this reason, the carrier indication field is never present in DCI formats monitored in the common search space.

As mentioned earlier, there is one device-specific search space per aggregation level and component carrier used for scheduling the PDSCH/PUSCH. This is illustrated in Figure 12.12, where PDSCH/PUSCH transmissions on component carrier 1 are scheduled using PDCCHs transmitted on component carrier 1. No carrier indicator is assumed in the device-specific search space for component carrier 1 as cross-carrier scheduling is not used. For component carrier 2, on the other hand, a carrier indicator is assumed in the device-specific search space as component carrier 2 is cross-carrier scheduled from PDCCHs transmitted on component carrier 1.

Search spaces for different component carriers may overlap in some subframes. In Figure 12.12, this happens for the device-specific search spaces for component carriers 3 and 4. The device will handle the two search spaces independently, assuming (in this example) a carrier indicator for component carrier 4 but not for component carrier 3. If the device-specific and common search spaces relating to different component carriers happen to overlap for some aggregation level when cross-carrier scheduling is configured, the device only needs to monitor the common search space. The reason for this is to avoid ambiguities; if the component carriers have different bandwidths a DCI format in the common search space may have the same payload size as another DCI format in the device-specific search space relating to another component carrier.

12.6 UPLINK CONTROL SIGNALING

Carrier aggregation implies that a device needs to transmit acknowledgments relating to simultaneous reception of data on multiple DL-SCHs, that is, transmission of more than two hybrid-ARQ acknowledgments in the uplink must be supported. There is also a need to provide CSI feedback relating to more than one downlink carrier.

As a baseline, all the feedback is transmitted on the primary component carrier, motivated by the need to support asymmetric carrier aggregation with the number of downlink carriers supported by a device being unrelated to the number of uplink carriers. Carrier aggregation therefore calls for an increase in the payload capability of the PUCCH. This was the motivation for PUCCH formats 3, 4, and 5, described in Chapter 7.

With the introduction of aggregation of up to 32 carriers in release 13, the number of hybrid-ARQ acknowledgments can be fairly larger. To avoid overloading a single uplink component carrier with PUCCH transmission, a device can be configured with two carrier groups, see Figure 12.13. In each group one component carrier is used to handle PUCCH transmissions from the device, resulting in two PUCCHs for uplink control signaling from one device. The resulting structure is similar to the dual connectivity structure described in Chapter 16 and many details are common, for example, power headroom reports and power scaling. Cross-carrier scheduling between the two groups are not supported.

12.6.1 HYBRID-ARQ ACKNOWLEDGMENTS ON PUCCH

Carrier aggregation implies an increase in the number of hybrid-ARQ acknowledgments to convey to the eNodeB. PUCCH format 1 can be used to support more than two bits in the uplink by using resource selection where part of the information is conveyed by the PUCCH resource selected and part by the bits transmitted on the selected resource (Figure 12.14). The details on how to select the resources are rather complex and depend on the duplexing scheme (FDD or TDD) and whether cross-carrier scheduling is used or not, although the basic idea is the same.

As an example, assume FDD with no cross-carrier scheduling. Furthermore, assume four bits are to be transmitted in the uplink, that is, there are 16 possible combinations of positive and negative acknowledgments. For each of these 16 combinations, one PUCCH resource out of four possible resources is selected and upon this resource two bits are transmitted.

Two of the PUCCH candidate resources to select from are derived from the first (E)CCE using the same rule as in absence of carrier aggregation (assuming that the scheduling

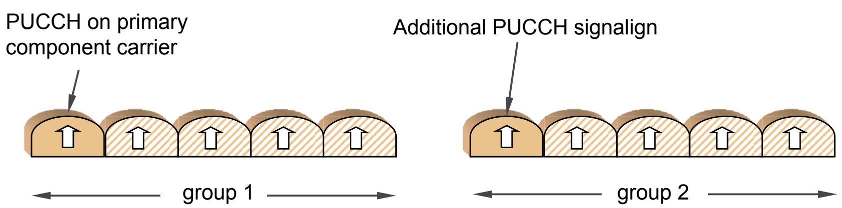

FIGURE 12.13

PUCCH on two uplink carriers in release 13.

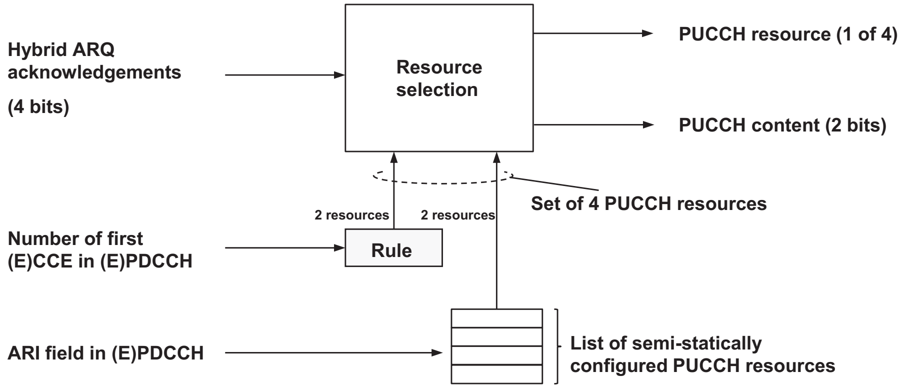

FIGURE 12.14

Example illustration of resource selection using PUCCH format 1 for carrier aggregation.

assignment is transmitted on, and relating to, the primary component carrier). The remaining two candidate resources are obtained by the *acknowledgment resource indicator* (ARI, see Section 6.4.6) on the (E)PDCCH pointing to a list of semi-statically configured PUCCH resources. For transmissions scheduled by the EPDCCH, the *acknowledgment resource offset* (ARO) is also included in the determination of the PUCCH resources. By the setting the ARO appropriately, the scheduler can ensure that multiple devices use noncolliding PUCCH resources. In presence of cross-carrier scheduling, all four resources are semi-statically configured and the ARI is not used.

For more than four bits, resource selection is less efficient and PUCCH formats 3, 4, or 5 are used. In PUCCH format 3, the set of multiple hybrid-ARQ acknowledgment bits (up to 10 or 20 bits for FDD or TDD, respectively, plus one bit reserved for scheduling requests) are jointly coded and transmitted as described in Chapter 7. PUCCH formats 4 and 5 support even larger number of bits. Not all devices support the newer PUCCH formats but for those that do support it, it can be used also for smaller numbers of acknowledgment bits.

The PUCCH resource to use is determined by the ARI. A device can be configured with four different resources for PUCCH format 3, 4, or 5 using RRC signaling. In the scheduling grant for a secondary carrier, the ARI informs the device which of the four resources to use. In this way, the scheduler can avoid PUCCH collisions between different devices by assigning them to different resources.

The set of hybrid-ARQ acknowledgments to transmit need to be coded into a set of bits and transmitted using PUCCH format 3, 4, or 5. Up to and including release 12, the ordering of the acknowledgments for the individual component carriers was determined by the semi-statically configured set of component carriers. Acknowledgment bits corresponding to configured but not scheduled component carriers are set to NAK. This means that there could be bits in a PUCCH message that relate to a component carrier not used in a particular subframe. It is a simple approach and avoids a mismatch between the device and eNodeB due to a missed scheduling assignment.

However, when increasing the number of component carriers up to 32 in release 13, the efficiency of the semi-static scheme is challenged. For a large number of configured component carriers out of which only a small number are scheduled to a particular device in a given subframe, the acknowledgment message can become fairly large compared to the number of component carriers used in the downlink. Furthermore, most of the bits in the acknowledgment message are already known as they correspond to component carriers not scheduled. This could negatively impact the decoding performance compared to a shorter message covering only the scheduled carriers. Therefore, the possibility to dynamically determine the set of component carriers to provide acknowledgments for such that only the scheduled carriers are included was introduced. Clearly, if a device would miss some scheduling assignments, the device and network would have different views on the number of acknowledgments to convey. The DAI, extended to cover also the carrier domain, is used to mitigate this disagreement.

12.6.2 CSI REPORTING ON PUCCH

CSI reports are typically needed for all the downlink component carriers. Since the baseline is to transmit all feedback on the primary component carrier, a mechanism handling multiple CSI reports is needed.

For periodic reporting, the basic principle is to configure the reporting cycles such that the CSI reports for the different component carriers are not transmitted simultaneously on PUCCH. Thus, CSI reports for different component carriers are transmitted in different subframes.

Handling of simultaneous channel-state information and acknowledgments varies a bit across the different releases. In release 10, simultaneous transmission of channel-state information and acknowledgments on PUCCH is not supported—neither for PUCCH format 2, nor for PUCCH format 3—and the CSI report is dropped. Release 11 and later releases, on the other hand, provide support for simultaneous transmission of acknowledgments and periodic CSI reports. The CSI bits are in this case concatenated with the acknowledgment bits and the scheduling request bit and transmitted using PUCCH format 3, 4, or 5. The PUCCH resource to use is determined by the ARI in the downlink control signaling, which selects the resource to use from a set of four resources preconfigured in the device by RRC signaling.

If the number of concatenated information bits is larger than 22 bits for PUCCH format 3 (the maximum number of information bits supported by PUCCH format 3), bundling of the acknowledgment bits are applied prior to concatenation in order to reduce the payload size. In case the payload still is larger than 22 bits, the CSI is dropped and only the acknowledgments (and potentially scheduling request) are transmitted. The process of bundling and dropping in case of a too large payload is illustrated in Figure 12.15. The same principle is used for PUCCH format 4 and 5 although with different limits on the number of bits. Furthermore, it is

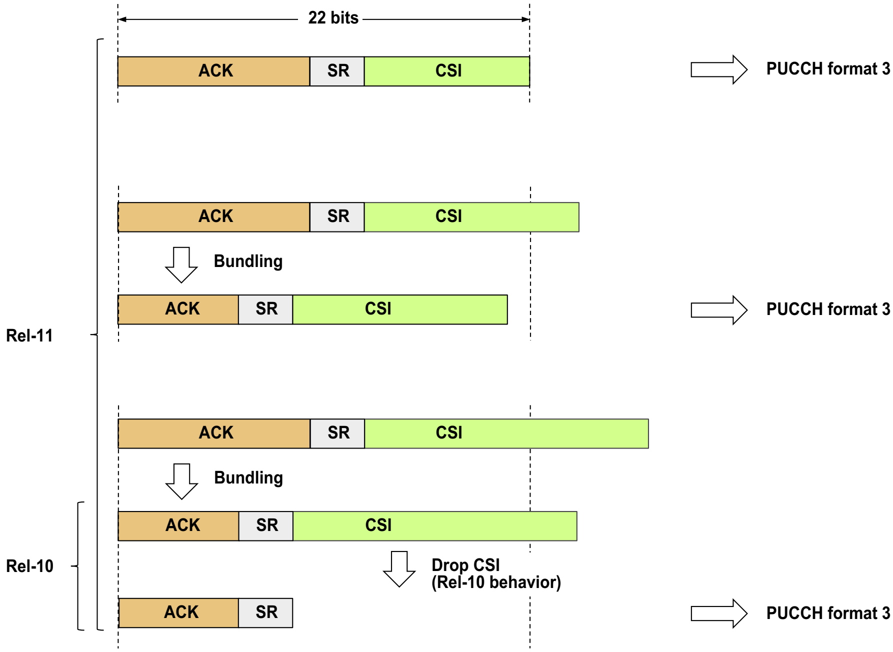

FIGURE 12.15

Multiplexing of acknowledgments, scheduling request, and CSI in release 11.

also possible to configure a device using PUCCH format 4/5 with *two* resources for these formats, one larger than the other. If the small resource results in a too high a code rate, the device uses the larger resource for PUCCH format 4/5.

12.6.3 CONTROL SIGNALING ON PUSCH

For carrier aggregation, control signaling is time multiplexed on one uplink component carrier only—that is, uplink control information on PUSCH cannot be split across multiple uplink component carriers. Apart from the aperiodic CSI reports, which are transmitted upon the component carrier that triggered the report, the primary component carrier is used for uplink control signaling if scheduled in the same subframe, otherwise one of the secondary component carriers is used.

For aperiodic CSI reporting, the CSI request field in the (E)PDCCH is extended to two bits (three bits in release 13), allowing for request of CSI reports for three (seven) combinations of downlink component carriers (the last bit combination represents no CSI request). Of these three (seven) alternatives, one is used to trigger a CSI report for the downlink component carrier associated with the uplink component carrier the scheduling grant relates to. The remaining alternatives point to configurable combinations of component carriers for which the CSI report should be generated. Thus, as an example, for a device capable of two downlink component carriers, aperiodic reports can, with the proper configuration, be requested for the primary component carrier, the secondary component carrier, or both.

12.7 TIMING ADVANCE AND CARRIER AGGREGATION

For carrier aggregation, there may be multiple component carriers transmitted from a single device. The simplest way of handling this is to apply the same timing-advance value for all uplink component carriers. This is also the approach taken in release 10. In release 11, additional flexibility is provided through the introduction of so-called timing-advance groups (TAGs) which allow different timing-advance commands for different groups of component carriers. One motivation for this could be interband carrier aggregation, where the different component carriers are received at different geographical locations, for example, by using remote radio heads for some of the bands but not others. Another example could be frequency-selective repeaters, repeating only some of the uplink component carriers.

Uplink component carriers are semi-statically grouped into timing-advance groups via RRC signaling (up to four groups can be configured). All component carriers in the same group are subject to the same timing-advance command.