CHAPTER

10 CHANNEL-STATE INFORMATION AND FULL-DIMENSION MIMO

The possibility for downlink channel-dependent scheduling—that is, selecting the downlink transmission configuration and related parameters depending on the instantaneous downlink channel condition, including the interference situation—is a key feature of LTE. As already mentioned, an important part of the support for downlink channel-dependent scheduling is *channel-state information* (CSI) provided by devices to the network, information on which the latter can base its scheduling decisions. CSI reports has been part of LTE since the first release but has evolved over the releases to support more advanced antenna configurations with enhancements for full-dimension MIMO (FD-MIMO) in release 13 being the latest example. This chapter describes the basics of CSI reporting and some of these enhancements, including the support for FD-MIMO.

10.1 CSI REPORTS

CSI reports provide the network with information about the current channel conditions. The CSI consists of one or several pieces of information:

- *Rank indicator* (RI), providing a recommendation on the transmission rank to use or, expressed differently, the number of layers that should preferably be used for DL-SCH transmission to the device. The RI is further discussed in Section 10.5.
- *Precoder matrix indicator* (PMI), indicating a preferred precoder to use for DL-SCH transmission, conditioned on the number of layers indicated by the RI. The precoder recommended by the device is not explicitly signaled but provided as an index into a set of predefined matrices, a so-called *codebook*. The PMI is discussed in Section 10.5 with enhancements for FD-MIMO in Section 10.6.
- *Channel-quality indicator* (CQI), representing the highest modulation-and-coding scheme that, if used, would mean a DL-SCH transmission using the recommended RI and PMI would be received with a block-error probability of at most 10%.
- *CSI-RS resource indicator* (CRI), used in conjunction with beam-formed CSI reference signals introduced in release 13. The CRI indicates the beam the device prefers in case the device is configured to monitor multiple beams, see Section 10.6.

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Together, a combination of the RI, PMI, CQI, and CRI forms a CSI report. Exactly what is included in a CSI report depends on the reporting mode the device is configured to be in. For example, RI and PMI do not need to be reported unless the device is in a spatial-multiplexing transmission mode. However, also given the transmission mode, there are different reporting configurations that typically differ as to what set of resource blocks the report is valid for and whether precoding information is reported or not. The type of information useful to the network also depends on the particular implementation and antenna deployment.

Although referred to as CSI, what a device delivers to the network are not explicit reports of the downlink channel state in terms of the radio channel. Rather, what the device delivers are *suggestions* on the transmission rank and precoding matrix to use, together with an indication of the highest possible modulation-and-coding scheme that the network should not exceed if it intends to keep the block-error probability below 10%.

Information about the actual modulation scheme and coding rate used for DL-SCH transmission as well as the set of resource blocks used for the transmission is always included in the downlink scheduling assignment. Hence, the eNodeB is free to follow the CSI report or to select transmission parameters on its own.

10.2 PERIODIC AND APERIODIC CSI REPORTS

There are two types of CSI reports in LTE, *aperiodic* and *periodic* reports, which are different in terms of how a report is triggered:

- Aperiodic CSI reports are delivered when explicitly requested by the network by means of the channel-state-request flag included in uplink scheduling grants (see Section 6.4.7). An aperiodic CSI report is always delivered using the PUSCH—that is, on a dynamically assigned resource.
- Periodic CSI reports are configured by the network to be delivered with a certain periodicity, possibly as often as once every 2 ms, on a semi-statically configured PUCCH resource. However, similar to hybrid-ARQ acknowledgments normally delivered on PUCCH, channel-state reports are "re-routed" to the PUSCH[1] if the device has a valid uplink grant.

Aperiodic and periodic reports, despite both providing estimates of the channel and interference conditions at the device, are quite different in terms of their detailed contents and the usage. In general, aperiodic reports are larger and more detailed than their periodic counterparts. There are several reasons for this. First, the PUSCH, upon which the aperiodic report is transmitted, is capable of a larger payload, and hence a more detailed report, than the PUCCH used for the periodic reports. Furthermore, as aperiodic reports are transmitted

[1]In release 10 and later, a device can be configured for simultaneous PUSCH and PUCCH transmission, in which case the periodic channel-state reports can remain on the PUCCH.

on a per-need basis only, the overhead from these reports is less of an issue compared to periodic reports. Finally, if the network requests a report it is likely that it will transmit a large amount of data to the device, which makes the overhead from the report less of an issue compared to a periodic report that is transmitted irrespective of whether the device in question is scheduled in the near future or not. Hence, as the structure and usage of aperiodic and periodic reports are different, they are described separately in the following, starting with aperiodic reports.

10.2.1 APERIODIC CSI REPORTS

Aperiodic CSI reports are transmitted on the PUSCH upon request by the network. Three aperiodic reporting modes, where each mode has several sub-modes depending on the configuration, are supported in LTE:

- Wideband reports, reflecting the average channel quality across the entire cell bandwidth with a single CQI value. Despite a single average CQI value being provided for the whole bandwidth, the PMI reporting is frequency selective. Frequency-selective reporting is obtained, for reporting purposes only, by dividing the overall downlink bandwidth (of each component carrier) into a number of equally sized *sub-bands*, where each sub-band consists of a set of consecutive resource blocks. The size of a sub-band, ranging from four to eight resource blocks, depends on the cell bandwidth. The PMI is then reported for each sub-band. For transmission modes supporting spatial multiplexing, the CQI and the PMI are calculated assuming the channel rank indicated by the RI, otherwise rank-1 is assumed. Wideband reports are smaller than their frequency-selective counterparts, but do not provide any information about the frequency domain.
- UE-selected reports, where the device selects the best M sub-bands and reports, in addition to the indices of the selected sub-bands, one CQI reflecting the average channel quality over the selected M sub-bands together with one wideband CQI reflecting the channel quality across the full downlink carrier bandwidth. This type of report thus provides frequency-domain information about the channel conditions. The sub-band size, ranging from two to four resource blocks, and the value of M, ranging from 1 to 6, depends on the downlink carrier bandwidth. Depending on the sub-mode configured, the PMI and RI are also provided as part of this type of report.
- Configured reports, where the device reports one wideband CQI reflecting the channel quality across the full downlink carrier bandwidth and one CQI per sub-band. The sub-band size depends on the downlink carrier bandwidth and is in the range of four to eight resource blocks. Depending on the sub-mode configured, the PMI and RI are also provided as part of this type of report.

The different aperiodic reporting modes are summarized in Table 10.1.

Table 10.1 Possible Aperiodic Reporting Modes for Different Transmission Modes

Transmission Mode		Reporting Mode								
		Wideband CQI			Frequency-Selective CQI					
					UE-Selected Sub-bands			Conf. Sub-bands		
		1-0: No PMI	1-1: Wideband PMI	1-2: Selective PMI	2-0: No PMI	2-1: Wideband PMI	2-2: Selective PMI	3-0: No PMI	3-1: Wideband PMI	3-2: Selective PMI
1	Single antenna, CRS	•[13]			•			•		
2	Transmit diversity	•[13]			•			•		
3	Open-loop spatial mux	•[13]			•			•		
4	Closed-loop spatial mux		•[13]	•			•		•	•[12]
5	Multi-user MIMO		•[13]						•	
6	Codebook-based beam-form		•[13]	•			•		•	•[12]
7	Single-layer trans., DM-RS	•[13]			•			•		
8	Dual-layer trans., DM-RS	•[13]	•[13]	•[10]	•[10]		•[10]	•[10]	•[10]	•[12]
9	Multi-layer trans., DM-RS	•[13]	•[13]	•[10]	•[10]		•[10]	•[10]	•[10]	•[12]
10	Multi-layer trans., DM-RS	•[13]	•[13]	•[11]	•[11]		•[11]	•[11]	•[11]	•[12]

The superscript indicates in which release a certain reporting mode was introduced.

10.2.2 PERIODIC CSI REPORTS

Periodic reports are configured by the network to be delivered with a certain periodicity. The periodic reports are transmitted on the PUCCH (unless the device has a simultaneous grant for PUSCH transmission and is not using simultaneous PUSCH and PUCCH transmission). The limited payload possible on PUCCH, compared to PUSCH, implies that the different types of information in a periodic report may not be possible to transmit in a single subframe. Therefore, some of the reporting modes will transmit one or several of the wideband CQI, including PMI, the RI, and the CQI for the UE-selected sub-bands at different time instants. Furthermore, the RI can typically be reported less often, compared to the reporting of PMI and CQI, reflecting the fact that the suitable number of layers typically varies on a slower basis, compared to the channel variations that impact the choice of precoder matrix and modulation-and-coding scheme.

Two periodic reporting modes, again with different sub-modes possible, are supported in LTE:

- *Wideband reports*. Reflect the average channel quality across the entire cell bandwidth with a single CQI value. If PMI reporting is enabled, a single PMI valid across the full bandwidth is reported.
- *UE-selected reports*. Although named in the same way as for aperiodic reports, the principle for UE-selected periodic reports is different. The total bandwidth (of a component carrier) is divided into one to four *bandwidth parts*, with the number of bandwidth parts obtained from the cell bandwidth. For each bandwidth part, the device selects the best sub-band within that part. The sub-band size ranges from four to eight resource blocks. Since the supported payload size of the PUCCH is limited, the reporting cycles through the bandwidth parts and in one subframe report the wideband CQI and PMI (if enabled) for that bandwidth part, as well as the best sub-band and the CQI for that sub-band. The RI (if enabled) is reported in a separate subframe.

The different periodic reporting modes are summarized in Table 10.2. Note that all PMI reporting, if enabled, is of wideband type. There is no support for frequency-selective PMI in periodic reporting, as the amount of bits would result in a too large overhead.

A typical use of periodic and aperiodic reporting could be to configure lightweight periodic CSI reporting on PUCCH, for example, to provide feedback of the wideband CQI and no PMI information (mode 1-0). Upon arrival of data to transmit in the downlink to a specific device, aperiodic reports could be requested as needed, for example, with frequency-selective CQI and PMI (mode 3-1).

10.3 INTERFERENCE ESTIMATION

Channel-state reports, irrespective of whether they are aperiodic or periodic, need measurements of the channel properties as well as the interference level.

Table 10.2 Possible Periodic Reporting Modes for Different Transmission Modes

Transmission Mode		Reporting Mode								
					Frequency-Selective CQI					
		Wideband CQI			UE-Selected Sub-bands			Conf. Sub-bands		
		1-0: No PMI	1-1: Wideband PMI	1-2: Selective PMI	2-0: No PMI	2-1: Wideband PMI	2-2: Selective PMI	3-0: No PMI	3-1: Wideband PMI	3-2: Selective PMI
1	Single antenna, CRS	•			•					
2	Transmit diversity	•			•					
3	Open-loop spatial mux	•			•					
4	Closed-loop spatial mux		•			•				
5	Multi-user MIMO		•			•				
6	Codebook-based beam-form		•			•				
7	Single-layer trans., DM-RS	•			•					
8	Dual-layer trans., DM-RS	•[10]	•[10]		•[10]	•[10]				
9	Multi-layer trans., DM-RS	•[10]	•[10]		•[10]	•[10]				
10	Multi-layer trans., DM-RS	•[11]	•[11]		•[11]	•[11]				

The superscript indicates in which release a certain reporting mode was introduced.

Measuring the channel gain is relatively straightforward and from the first release, it is well specified which subframe the CSI report relates to. The reference signal which the channel-gain estimate is based upon, CRS or CSI-RS, depends on the transmission mode. For transmission modes already supported in release 8/9, the cell-specific reference signals are used, while for transmission modes 9 and 10, introduced in releases 10 and 11, respectively, the CSI-RS is used.

Measuring the interference level, which is required in order to form a relevant CSI, is more cumbersome and the measurement is greatly affected by the transmission activity in neighboring cells. LTE release 10 and earlier does not specify how to measure the interference level and leave the details for the implementation. However, in practice, interference is measured as the noise on the cell-specific reference signals—that is, the residual after subtracting the reference signal from the received signal in the appropriate resource elements is used as an estimate of the interference level. At low loads, this approach unfortunately often results in overestimating the interference level as the measurements are dominated by CRS transmissions in neighboring cells (assuming the same CRS positions in the neighboring cells), irrespective of the actual load in those cells. Furthermore, the device may also choose to average the interference level across multiple subframes[2], further adding to the uncertainty on how the interference is measured by the device.

To address these shortcomings and to better support various CoMP schemes, transmission mode 10, introduced in release 11, provides tools for the network to control on which resource elements the interference is measured. The basis is a so-called *CSI interference measurement* (CSI-IM) configuration, where a CSI-IM configuration is the set of resource elements in one subframe the device should use for measuring interference. The received power in the resource elements corresponding to the CSI-IM configuration is used as an estimate of the interference (and noise). The single subframe in which the interference should be measured is also specified, thereby avoiding device-specific, and to the network unknown, interference averaging across subframes.

Configuring a CSI-IM is done in a similar manner as a CSI-RS and the same set of configurations is available, see Chapter 6. In practice a CSI-IM resource would typically correspond to a CSI-RS resource in which nothing is transmitted from the cell or, in the general case, from a certain transmission point. Thus, in practice the CSI-IM resource will typically be covered by the set of zero-power CSI-RS resources configured for the device. However, CSI-IM and zero-power CSI-RS serve different purposes. CSI-IM is defined in order to specify a set of resource elements on which a device should measure the interference level while zero-power CSI-RS is defined in order to specify a set of resource elements avoided by the PDSCH mapping.

Since the CSI-IM does not collide with the CRS in neighboring cells but rather the PDSCH (assuming a synchronized network), the interference measurement better reflects the

[2]In releases 10 and later, there is a possibility to limit the interference averaging to different subsets of subframes in order to improve the support for heterogeneous deployments, see Chapter 14.

transmission activity in neighboring cells, leading to a more accurate interference estimate at low loads. Hence, with the channel conditions estimated from the CSI-RS and the interference situation estimated from the CSI-IM, the network has detailed control of the interference situation the CSI report reflects.

In some scenarios, the eNodeB benefits from *multiple* CSI reports, derived under different interference hypotheses. Therefore, release 11 provides support for up to four *CSI processes* in a device, where a CSI process is defined by one CSI-RS configuration and one CSI-IM configuration. CSI is then reported separately for each process[3]. A more in depth discussion on the usage of CSI processes to support CoMP is found in Chapter 13.

10.4 CHANNEL-QUALITY INDICATOR

Having discussed CSI reporting in general it is appropriate to discuss the different information fields in a CSI report. The CQI provides an estimate of the highest modulation-and-coding scheme that, if used with the recommended RI and PMI, would result in a block-error probability for the DL-SCH transmissions of at most 10%. The reason to use CQI as a feedback quantity instead of, for example, the signal-to-noise ratio, is to account for different receiver implementations in the device. Also, basing the feedback reports on CQI instead of signal-to-noise ratio simplifies the testing of devices; a device delivering data with more than 10% block-error probability when using the modulation-and-coding scheme indicated by the CQI would fail the test. As is discussed later, multiple CQI reports, each representing the channel quality in a certain part of the downlink spectrum, can be part of the CSI.

The modulation-and-coding scheme used for DL-SCH transmission can, and often will, differ from the reported CQI as the scheduler needs to account for additional information not available to the device when recommending a certain CQI. For example, the set of resource blocks used for the DL-SCH transmission also needs to account for other users. Furthermore, the amount of data awaiting transmission in the eNodeB also needs to be accounted for. There is no need to select a very high data rate, even if the channel conditions would permit this, if there is only a small amount of data to transmit and a small number of resource blocks with robust modulation is sufficient.

10.5 RANK INDICATOR AND PRECODER MATRIX INDICATOR

The multi-antenna-related part of the CSI consists of the RI and the PMI. This section will describe the basic RI and PMI reporting and the associated codebooks and in Section 10.6 the extension added in release 13 to handle FD-MIMO, including the additional codebooks and the CSI-RS resource indicator (CRI).

[3]It is possible to configure *rank inheritance*, in which case the rank reported by one CSI process is inherited from another CSI process.

The RI is only reported by devices that are configured in one of the spatial-multiplexing transmission modes. There is at most one RI reported (for a particular CSI process on a particular component carrier, see later for details), valid across the full bandwidth—that is, the RI is frequency nonselective. Note that frequency-selective transmission rank is not possible in LTE as all layers are transmitted on the same set of resource blocks.

The PMI provides an indication to the eNodeB of the preferred precoder to use conditioned on the number of layers indicated by the RI. The precoder recommendation may be frequency selective, implying that the device may recommend different precoders for different parts of the downlink spectrum, or frequency nonselective.

With regard to the precoder-related recommendations, the network has two choices:

- The network may follow the latest device recommendation, in which case the eNodeB only has to confirm (a one-bit indicator in the downlink scheduling assignment) that the precoder configuration recommended by the device is used for the downlink transmission. On receiving such a confirmation, the device will use its recommended configuration when demodulating and decoding the corresponding DL-SCH transmission. Since the PMI computed in the device can be frequency selective, an eNodeB following the precoding matrix recommended by the device may have to apply different precoding matrices for different (sets of) resource blocks.
- The network may select a different precoder, information about which then needs to be explicitly included in the downlink scheduling assignment. The device then uses this configuration when demodulating and decoding the DL-SCH. To reduce the amount of downlink signaling, only a single precoding matrix can be signaled in the scheduling assignment, implying that, if the network overrides the recommendation provided by the device, the precoding is frequency nonselective. The network may also choose to override the suggested transmission rank only.

The precoder recommended by the device is not explicitly signaled but provided as an index into a set of predefined matrices, a so-called *codebook*. The set of matrices from which the device selects the preferred precoder depends on the number of antenna ports. Although the specifications do not mandate any particular antenna arrangement, the assumptions on antenna arrangements affect the codebook design. These assumptions have varied across the different releases, impacting the characteristics of the resulting codebook as illustrated in Figure 10.1.

For two or four antenna ports (irrespective of whether CRS or DM-RS is used for demodulation), the codebook is given by the set of precoders for codebook-based precoding (see Section 10.3.2). This is a natural choice for the multi-antenna transmission modes based on cell-specific reference signals (transmission modes 4, 5, and 6) as the network in these modes must use a codebook from this set. For simplicity the same codebook is used for CSI reporting for transmission modes 8, 9, and 10 using demodulation-specific reference signals, even though the network in this case can use any precoders as the precoder used is transparent

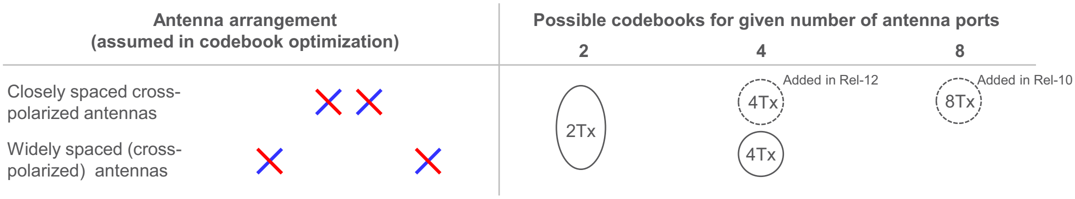

FIGURE 10.1

Assumptions on antenna arrangements for different codebooks.

to the device. The four-antenna codebook is derived under the assumption of uncorrelated fading across the antennas, or, expressed differently, widely-spaced antennas.

For eight antenna ports, introduced in release 10 and supported in transmission modes 9 and 10 relying on demodulation-specific reference signals, a somewhat different approach for the codebook design than the two and four antenna cases in previous releases was taken. The assumption on uncorrelated fading across the antennas made in previous releases is less realistic as a more typical antenna arrangement is closely spaced cross-polarized antennas. Therefore, the codebook is tailored for closely spaced cross-polarized antenna elements (see Figure 10.2) and also covers the case of eight closely spaced linearly polarized antennas. All precoders in the codebook can be factorized as $W = W_1 \cdot W_2$, where the possible entries for W_1 model long-term/wideband aspects such as beam-forming while the possible entries of W_2 address short-term/frequency-selective properties such as polarization properties. One reason for factorizing the codebook is to simplify implementation as the device may apply different (time-domain) filtering to the two parts when forming the PMI. In release 12, an alternative

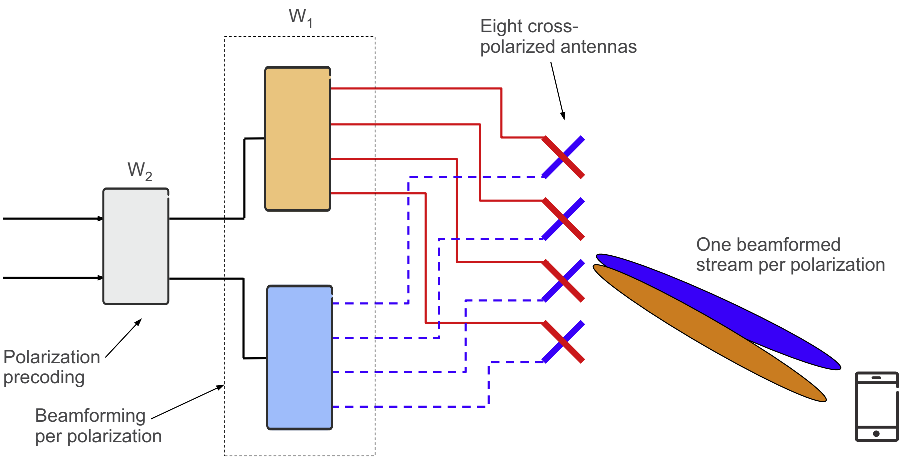

FIGURE 10.2

Illustration of the eight-antenna codebook.

four-antenna codebook following the same design principle as the eight-antenna one was introduced.

In release 13, the CSI reporting in general and the codebook design in particular was further enhanced to handle a larger number of antenna ports. This is described in Section 10.6.

Finally, for two, four, and eight antenna ports, the network can restrict the set of matrices from which the device can select the recommended precoder, so-called codebook subset restriction, to avoid reporting precoders that are not useful in the antenna setup actually used.

10.6 FULL-DIMENSION MIMO

The CSI reporting described in the previous sections covered up to eight antenna ports. Furthermore, although not explicitly stated in the specifications, the focus from a beam-forming perspective has primarily been on one-dimensional beam-forming in the azimuth domain. However, with tight integration of antenna elements and RF components, such as power amplifiers and transceivers, a significantly larger number of controllable antenna elements than eight is feasible. This can enable new advanced antenna solutions, for example, massive multi-user MIMO, two-dimensional beam-forming, and dynamic device-specific down-tilt. In principle, as the specifications described antenna ports but not the antenna elements as such, implementation-specific realization of many of these advanced antenna solutions is possible. However, to better exploit a larger number of antenna elements, release 13 increased the number of antenna ports to 16 and improved the CSI feedback taking the larger number of antenna ports into account. The number of sounding reference signals was also increased as mentioned in Chapter 6 to better support a larger number of users.

10.6.1 CSI FEEDBACK FOR MASSIVE ANTENNA ARRANGEMENTS

CSI feedback for a large number of antenna elements can be solved in many ways, grouped into two main categories: per-element reporting and per-beam reporting. Both of these approaches are supported in release 13 with the reporting class configured through RRC signaling.

Per-element reporting is the approach used in previous releases. Each CSI reference signal is mapped to (a fixed group of) antenna elements and the feedback consists of high-dimensional precoder matrices based on measurements on all the different CSI reference signals. The amount of CSI reference signals would in this case be determined by the number of antenna elements, and not by the number of simultaneously served devices, making this approach primarily suitable for a modest number of antennas. In LTE per-element reporting is referred to as CSI reporting class A.

Per-beam reporting implies that each CSI reference signal is beam-formed (or precoded) using all the antenna elements. The device measures on the beam-formed CSI reference signals it has been configured to measure upon and, among those beams, recommends a suitable beam for subsequent data transmission. The amount of CSI reference signals, the device channel estimator complexity, and the associated feedback would in this case be determined by the number of simultaneous beams rather than the number of antenna elements, making this approach primarily suitable for a very large number of antenna elements. Since each CSI reference signal is beam-formed, this approach can have coverage benefit compared to the per-element approach but potentially also be less robust as the device does not estimate the full channel. In LTE per-beam reporting is known as CSI reporting class B.

The two approaches are illustrated in Figure 10.3 and described in more detail in the following section.

10.6.2 CSI REPORTING CLASS A

CSI reporting class A is a direct extension of the CSI reporting framework in earlier releases to a larger number of antenna ports. Each antenna element transmits a unique CSI reference signal per polarization. Based on measurements on these reference signals the devices computes a recommended precoder as well as RI and CQI conditioned on the precoder.

The precoders available in earlier releases were developed assuming a one-dimensional array as illustrated in Figure 10.1, although this is not explicitly stated in the specifications. For a two-dimensional array a given number of antenna elements can be arranged in many different ways with different arrangements being preferred in different deployments. To handle this, a codebook parametrized by the number of horizontal and vertical antenna ports was selected for release 13, capable of handling the antenna arrangements shown in Figure 10.4. The device is informed about the codebook to use through RRC signaling.

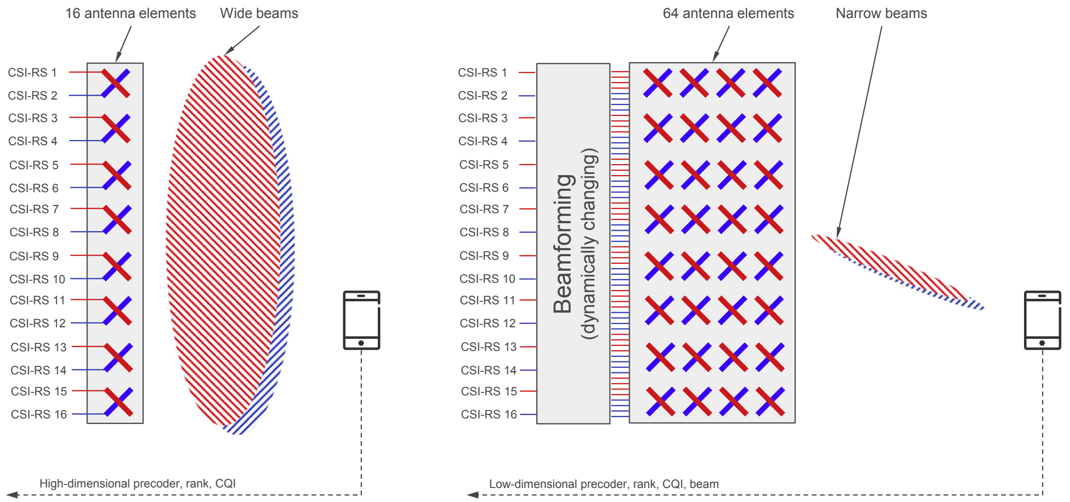

FIGURE 10.3

Illustration of per-element (left) and per-beam (right) CSI-RS transmission.

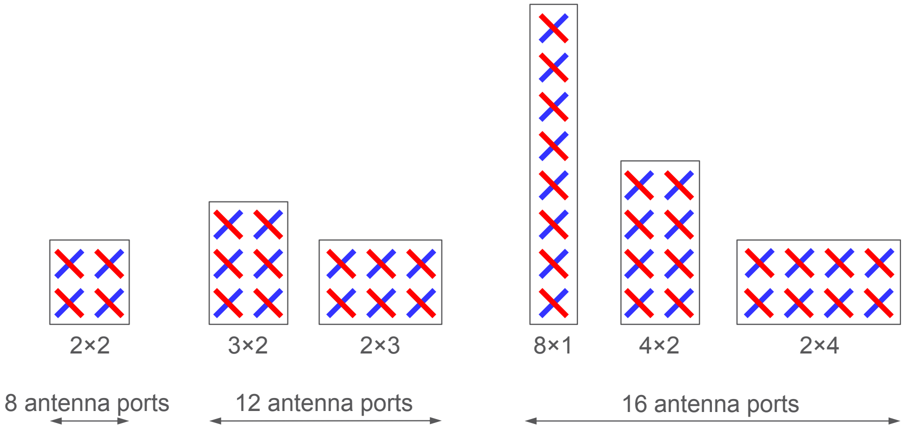

FIGURE 10.4

Supported two-dimensional antenna configurations.

The same codebook structure is used for 8, 12, and 16 antenna ports, following the principles in release 10 with all precoders in the codebook factorized as $W = W_1 \cdot W_2$, where W_1 model long-term/wideband aspects and W_2 address short-term/frequency-selective properties. The details of the codebook structure can be found in [26], but in essence the DFT structure used results in a grid-of-beams codebook. It is also prepared for extensions to a larger number of antenna elements in future releases.

Transmitting one CSI reference signal per element and polarization (or small group of elements) may lead to coverage problems as there is no array gain, calling for the possibility of power boosting to compensate. The possibility for length-four orthogonal cover code, in addition to the length-two part of earlier release, was introduced with this in mind. The longer the cover code, the larger the possibility to "borrow" power between CSI reference signals.

10.6.3 CSI REPORTING CLASS B

CSI reporting class B is a new framework in release 13, different from the per-element approach used in previous releases. In this approach the device measures on a relatively small number of beam-formed CSI reference signals. In principle, arbitrarily large antenna arrays can be used, unlike class A reporting which is limited to the 16 antenna pots.

Up to eight CSI-RS resources can be configured in the device per CSI process where each CSI-RS resource consists of 1, 2, 4, or 8 antenna ports in one beam, see Figure 10.5 for an illustration. The device will measure on each of the CSI-RS resources and report back the recommended beam in the form of a CRI (CSI-RS resource index), along with CQI, PMI, and RI under the assumption of the preferred beam being used for transmission. The same beam is used across the whole bandwidth—that is, the CRI is frequency nonselective unlike CQI and PMI, which can vary across the frequency range. As an example, if the topmost red beam is the

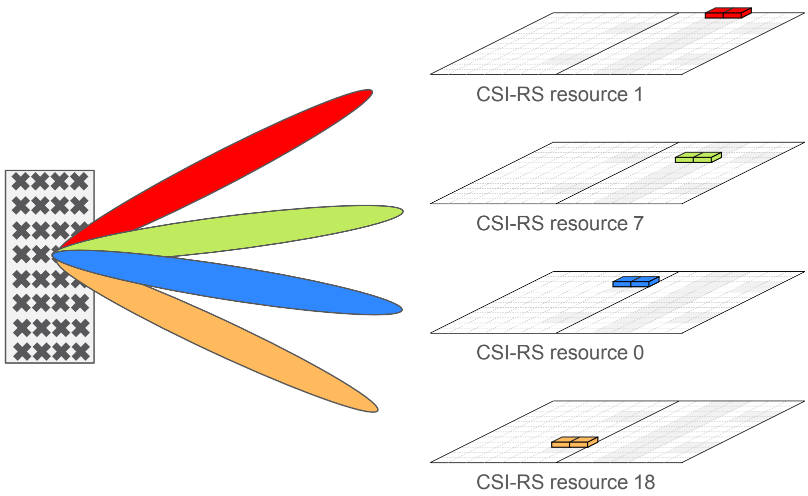

FIGURE 10.5

Example of CSI-RS resources for beam measurements.

preferred one from a device perspective, the device will report CRI equal to one, along with preferred CQI, PMI, and RI conditioned on the topmost beam being used for transmission. For PMI reporting, the 2, 4, or 8 antenna codebooks defined in previous releases is used.

In case a single CSI-RS resource of 1, 2, 4, or 8 antenna ports is configured, a codebook selecting pairs of antenna ports is used. Each pair corresponds to a beam and the device selects a preferred beam, possibly per sub-band (unlike the CRI case described earlier where the same beam is used across all sub-bands). This approach provides a faster feedback of the preferred beam than the CRI approach described earlier as the PMI, which points in to the codebook, can be reported more frequently than the CRI.

Beam-formed CSI reference signals are beneficial from a coverage perspective and can be used with very large antenna arrays. However, it also poses the challenges of beam finding and beam tracking. Upon entering a new cell, the direction in which to transmit the CSI-RS needs to be determined and updated as the device moves within the cell. There are multiple ways of addressing this challenge.

One possibility is to transmit discovery reference signals in a large set of fixed beams and use discovery signal measurement reports from the device to determine a relevant direction. Since the discovery reference signals are transmitted periodically, the eNodeB would obtain continuous updates on the "best" beam. However, as the discovery signal periodicity is fairly large, the method is mainly suitable for slowly moving devices. A similar behavior can be obtained by configuring (multiple) resources to measure upon in the device and vary the directions in which to transmit the beam-formed CSI reference signals. If inter-subframe averaging of the interference measurements is turned off, which is possible in release 13, an instantaneous CSI measurement is achieved and the eNodeB can determine which directions resulted in "high" CSI values and hence correspond to promising transmission directions.

Uplink sounding and channel reciprocity can also be used for beam finding, either alone or in combination with measurements from the device. Reciprocity is often associated with TDD systems, but the long-term statistics, for example, angle-of-arrival, is typically reciprocal also in the case of FDD which is sufficient for beam finding.[4] The additional sounding capacity available in release 13, mentioned in Chapter 7, was partially added with this in mind.

Tracking of beams could, for example, be done by configuring multiple CSI resources in the device, including the "best" beam and a couple of surrounding beams. If the set of resources in the device updated when needed such that it always includes the "best" beam and the surrounding beams, it is possible to track beam changes. As the CSI reporting framework is fairly flexible, there are other possibilities as well. Also in this case uplink sounding can be exploited.

[4]Short-term properties such as the instantaneous channel impulse response are not reciprocal in FDD systems, but this does not matter in this case.