CHAPTER

# Uplink Power and Timing Control

# 15

Uplink power control and uplink timing control are the topics of this chapter. Power control serves the purpose of controlling the interference, mainly towards other cells as transmissions within the same cell typically are orthogonal. Timing control ensures that different device are received with the same timing, a prerequisite to maintain orthogonality between different transmissions.

## 15.1 UPLINK POWER CONTROL

NR uplink power control is the set of algorithms and tools by which the transmit power for different uplink physical channels and signals is controlled to ensure that they, to the extent possible, are received by the network at an appropriate power level. In the case of an uplink physical channel, the appropriate power is simply the received power needed for proper decoding of the information carried by the physical channel. At the same time, the transmit power should not be unnecessarily high as that would cause unnecessarily high interference to other uplink transmissions.

The appropriate transmit power will depend on the channel properties, including the channel attenuation and the noise and interference level at the receiver side. It should also be noted that the required received power is directly dependent on the data rate. If the received power is too low one can thus either increase the transmit power or reduce the data rate. In other words, at least in the case of PUSCH transmission, there is an intimate relationship between power control and link adaptation (rate control).

Similar to LTE power control [28], NR uplink power control is based on a combination of:

- *Open-loop* power control, including support for *fractional path-loss compensation*, where the device estimates the uplink path loss based on downlink measurements and sets the transmit power accordingly.
- *Closed-loop* power control based on explicit power-control commands provided by the network. In practice, these power-control commands are determined based on prior network measurements of the received uplink power, thus the term "*closed loop.*"

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The main difference, or rather extension, of NR uplink power control is the possibility for beam-based power control (see Section 15.1.2).

### 15.1.1 BASELINE POWER CONTROL

Power-control for PUSCH transmissions can, somewhat simplified, be described by the following expression:

$$P_{\mathrm{PUSCH}} = min\{P_{CMAX}, P_0(j) + \alpha(j) \cdot PL(q) + 10 \cdot log_{10}(2^{\mu} \cdot M_{RB}) + \Delta_{TF} + \delta(l)\} \qquad (15.1)$$

where

- $P_{\mathrm{PUSCH}}$ is the PUSCH transmit power;
- $P_{CMAX}$ is the maximum allowed transmit power per carrier;
- $P_0(.)$ is a network-configurable parameter that can, somewhat simplified, be described as a target received power;
- $PL(.)$ is an estimate of the uplink path loss;
- $\alpha(.)$ is a network-configurable parameter related to fractional path-loss compensation;
- $\mu$ relates to the subcarrier spacing $\Delta f$ used for the PUSCH transmission. More specifically, $\Delta f = 2^{\mu} \cdot 15$ kHz;
- $M_{RB}$ is the number of resource blocks assigned for the PUSCH transmission;
- $\Delta_{TF}$ relates to the modulation scheme and channel-coding rate used for the PUSCH transmission;[1]
- $\delta(.)$ is the power adjustment due to the closed-loop power control.

The above expression describes uplink power control per carrier. If a device is configured with multiple uplink carriers (carrier aggregation and/or supplementary uplink), power control according to expression (15.1) is carried out separately for each carrier. The $min\{P_{CMAX}, \ldots\}$ part of the power-control expression then ensures that the power per carrier does not exceed the maximum allowed transmit power per carrier. However, there will also be a limit on the total device transmit power over all configured uplink carriers. In order to stay below this limit there will, in the end, be a need to coordinate the power setting between the different uplink carriers (see further Section 15.1.4). Such coordination is needed also in the case of LTE/NR dual-connectivity.

We will now consider the different parts of the above power control expression in somewhat more detail. When doing this we will initially ignore the parameters $j$, $q$, and $l$. The impact of these parameters will be discussed in Section 15.1.2.

The expression $P_0 + \alpha \cdot PL$ represents basic open-loop power control supporting fractional path-loss compensation. In the case of full path-loss compensation, corresponding to $\alpha = 1$, and under the assumption that the path-loss estimate $PL$

[1]The abbreviation TF = transport format, a term used in earlier 3GPP technologies but not used explicitly for NR.

is an accurate estimate of the uplink path loss, the open-loop power control adjusts the PUSCH transmit power so that the received power aligns with the "target received power" $P_0$. The quantity $P_0$ is provided as part of the power-control configuration and would typically depend on the target data rate but also on the noise and interference level experienced at the receiver.

The device is assumed to estimate the uplink path loss based on measurements on some downlink signal. The accuracy of the path-loss estimate thus partly depends on what extent downlink/uplink reciprocity holds to. Especially, in the case of FDD operation in paired spectra, the path-loss estimate will not be able to capture any frequency-dependent characteristics of the path loss.

In the case of fractional path-loss compensation, corresponding to $\alpha < 1$, the path loss will not be fully compensated for and the received power will even on average vary depending on the location of the device within the cell, with lower received power for devices with higher path loss, in practice for devices at larger distance from the cell site. This must then be compensated for by adjusting the uplink data rate accordingly.

The benefit of fractional path-loss compensation is reduced interference to neighbor cells. This comes at the price of larger variations in the service quality, with reduced data-rate availability for devices closer to the cell border.

The term $10 \cdot log(2^{\mu} \cdot M_{RB})$ reflects the fact that, everything else unchanged, the received power, and thus also the transmit power, should be proportional to the bandwidth assigned for the transmission. Thus, assuming full path-loss compensation ($\alpha = 1$), $P_0$ can more accurately be described as a *normalized* target received power. Especially, assuming full path-loss compensation, $P_0$ is the target received power assuming transmission over a single resource block with 15 kHz numerology.

The term $\Delta_{TF}$ tries to model how the required received power varies when the number of information bits per resource element varies due to different modulation schemes and channel-coding rates. More precisely

$$\Delta_{TF} = 10 \cdot log\left(\left(2^{1.25 \cdot \gamma} - 1\right) \cdot \beta\right) \tag{15.2}$$

where $\gamma$ is the number of information bits in the PUSCH transmission, normalized by the number of resource elements used for the transmission not including resource elements used for demodulation reference symbols.

The factor $\beta$ equals 1 in the case of data transmission on PUSCH but can be set to a different value in the case that the PUSCH carries layer-1 control signaling (UCI).[2]

It can be noted that, ignoring the factor $\beta$, the expression for $\Delta_{TF}$ is essentially a rewrite of the Shannon channel capacity $C = W \cdot log_2(1 + SNR)$ with an additional factor 1.25. In other words, $\Delta_{TF}$ can be seen as modeling link capacity as 80% of Shannon capacity.

[2]Note that one could equally well have described this as a separate term $10 \cdot log(\beta)$ applied when PUSCH carries UCI.

The term $\Delta_{TF}$ is not always included when determining the PUSCH transmit power.

- The term $\Delta_{TF}$ is only used for single-layer transmission, that is, $\Delta_{TF} = 0$ in the case of uplink multi-layer transmission;
- The term $\Delta_{TF}$ can, in general, be disabled. $\Delta_{TF}$ should, for example, not be used in combination with fractional power control. Adjusting the transmit power to compensate for different data rates would counteract any adjustment of the data rate to compensate for the variations in received power due to fractional power control as described above.

Finally, the term $\delta(.)$ is the power adjustment related to closed-loop power control. The network can adjust $\delta(.)$ by a certain step given by a *power-control command* provided by the network, thereby adjusting the transmit power based on network measurements of the received power. The power control commands are carried in the TPC field within uplink scheduling grants (DCI formats 0−0 and 0−1). Power control commands can also be carried jointly to multiple devices by means of DCI format 2−2. Each power control command consists of 2 bits corresponding to four different update steps (−1 dB, 0 dB, +1 dB, +3 dB). The reason for including 0 dB as an update step is that a power-control command is included in every scheduling grant and it is desirable not to have to adjust the PUSCH transmit power for each grant.

## 15.1.2 BEAM-BASED POWER CONTROL

In the discussion above we ignored the parameter $j$ for the open-loop parameters $P_0(.)$ and $\alpha(.)$, the parameter $q$ in the path loss estimate $PL(.)$, and the parameter $l$ in the closed-loop power adjustment $\delta(.)$. The primary aim of these parameters is to take beam-forming into account for the uplink power control.

### *15.1.2.1 Multiple Path-Loss-Estimation Processes*

In the case of uplink beam-forming, the uplink-path-loss estimate $PL(q)$ used to determine the transmit power according to expression (15.1) should reflect the path loss, including the beam-forming gains, of the uplink beam pair to be used for the PUSCH transmission. Assuming beam correspondence, this can be achieved by estimating the path loss based on measurements on a downlink reference signal transmitted over the corresponding downlink beam pair. As the uplink beam used for the transmission pair may change between PUSCH transmissions, the device may thus have to retain multiple path-loss estimates, corresponding to different candidate beam pairs, in practice, path-loss estimates based on measurements on different downlink reference signals. When actual PUSCH transmission is to take place over a specific beam pair, the path-loss estimate corresponding to that beam pair is then used when determining the PUSCH transmit power according to the power-control expression (15.1).

This is enabled by the parameter $q$ in the path-loss estimate $PL(q)$ of Eq. (15.1). The network configures the device with a set of downlink reference signals (CSI-RS or SS block) on which path loss is to be estimated, with each reference signal being associated with a specific value of $q$. In order not to put too high requirements on the device, there can be at most four parallel path-loss-estimation processes, each corresponding to a specific value of $q$. The network also configures a mapping from the possible SRI values provided in the scheduling grant to the up to four different values of $q$. In the end there is thus a mapping from each of the possible SRI values provided in the scheduling grant to one of up to four configured downlink reference signals and thus, indirectly, a mapping from each of the possible SRI values to one of up to four path-loss estimates reflecting the path loss of a specific beam pair. When a PUSCH transmission is scheduled by a scheduling grant including SRI, the path-loss estimate associated with that SRI is used when determining the transmit power for the scheduled PUSCH transmission.

The procedure is illustrated in Fig. 15.1 for the case of two beam pairs. The device is configured with two downlink reference signals (CSI-RS or SS block) that in practice will be transmitted on the downlink over a first and second beam pair, respectively. The device is running two path-loss-estimation processes in parallel, estimating the path loss $PL(1)$ for the first beam pair based on measurements on reference signal RS-1 and the path loss $PL(2)$ for the second beam pair based on measurements on reference-signal RS-2. The parameter $q$ associates SRI = 1 with RS-1 and thus indirectly with $PL(1)$. Likewise, SRI = 2 is associated with RS-2 and thus indirectly with $PL(2)$. When the device is scheduled for PUSCH transmission with the SRI of the scheduling grant set to 1, the transmit power of the scheduled PUSCH transmission is determined based on the path-loss estimate $PL(1)$ that is, the path-loss estimate based on measurements on RS-1. Thus, assuming beam correspondence the path-loss estimate reflects the path loss of the beam pair over which the PUSCH is transmitted. If the device is instead scheduled for PUSCH transmission with SRI = 2, the path-loss estimate $PL(2)$, reflecting the path loss of the beam pair corresponding to SRI = 2, is used to determine the transmit power for the scheduled PUSCH transmission.

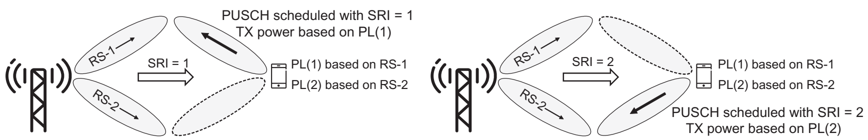


**FIGURE 15.1**

Use of multiple power-estimation processes to enable uplink power control in the case of dynamic beam management.

#### 15.1.2.2 Multiple Open-Loop-Parameter Sets

In the PUSCH power-control expression (15.1), the open-loop parameters $P_0$ and $\alpha$ are associated with a parameter $j$. This simply reflects that there may be multiple open-loop-parameter pairs $\{P_0, \alpha\}$. Partly, different open-loop parameters will be used for different types of PUSCH transmission (random-access "message 3" transmission, see Section 16.2, grant-free PUSCH transmissions, and scheduled PUSCH transmissions). However, there is also a possibility to have multiple pairs of open-loop parameter for scheduled PUSCH transmission, where the pair to use for a certain PUSCH transmission can be selected based on the SRI similar to the selection of path-loss estimates as described above. In practice this implies that the open-loop parameters $P_0$ and $\alpha$ will depend on the uplink beam.

For the power setting of random-message 3, which in the NR specification corresponds to $j = 0$, $\alpha$ always equals 1. In other words, fractional power control is not used for message-3 transmission. Furthermore, the parameter $P_0$ can, for message 3, be calculated based on information in the random-access configuration.

For other PUSCH transmissions the device can be configured with different open-loop-parameter pairs $\{P_0(j), \alpha(j)\}$, corresponding to different values for the parameter $j$. Parameter pair $\{P_0(1), \alpha(1)\}$ should be used in the case of grant-free PUSCH transmission, while the remaining parameter pairs are associated with scheduled PUSCH transmission. Each possible value of the SRI that can be provided as part of the uplink scheduling grant is associated with one of the configured open-loop-parameter pairs. When a PUSCH transmission is scheduled with a certain SRI included in the scheduling grant, the open-loop parameters associated with that SRI are used when determining the transmit power for the scheduled PUSCH transmission.

#### 15.1.2.3 Multiple Closed-Loop Processes

The final parameter is the parameter $l$ for the closed-loop process. PUSCH power control allows for the configuration of two independent closed-loop processes, associated with $l = 1$ and $l = 2$, respectively. Similar to the possibility for multiple path-loss estimates and multiple open-loop-parameter sets, the selection of $l$, that is, the selection of closed-loop process, can be tied to the SRI included in the scheduling grant by associating each possible value of the SRI to one of the closed-loop processes.

### 15.1.3 POWER CONTROL FOR PUCCH

Power control for PUCCH follows essentially the same principles as power control for PUSCH, with some minor differences.

First, for PUCCH power control, there is no fractional path-loss compensation, that is, the parameter $\alpha$ always equals one.

Furthermore, for PUCCH power control, the closed-loop power control commands are carried within DCI formats 1−0 and 1−1, that is, within downlink scheduling assignments rather than within uplink scheduling grants, which is the case for PUSCH power control. One reason for uplink PUCCH transmissions is the transmission of hybrid-ARQ acknowledgments as a response to downlink transmissions. Such downlink transmissions are typically associated with downlink scheduling assignments on PDCCH and the corresponding power-control commands could thus be used to adjust the PUCCH transmit power prior to the transmission of the hybrid-ARQ acknowledgments. Similar to PUSCH, power-control commands can also be carried jointly to multiple devices by means of DCI format 2−2.

### 15.1.4 POWER CONTROL IN THE CASE OF MULTIPLE UPLINK CARRIERS

The above procedures describe how to set the transmit power for a given physical channel in the case of a single uplink carrier. For each such carrier there is a maximum allowed transmit power $P_{CMAX}$ and the $min\{P_{CMAX},\ldots\}$ part of the power-control expression ensures that the per-carrier transmit power of a carrier does not exceed power $P_{CMAX}$.[3]

In many cases, a device is configured with multiple uplink carriers:

- Multiple uplink carriers in a carrier aggregation scenario;
- An additional supplementary uplink carrier in the case of SUL.

In addition to the maximum per-carrier transmit power $P_{CMAX}$, there is a limit $P_{TMAX}$ on the total transmitted power over all carriers. For a device configured for NR transmission on multiple uplink carriers, $P_{CMAX}$ should obviously not exceed $P_{TMAX}$. However, the sum of $P_{CMAX}$ over all configured uplink carriers may very well, and often will, exceed $P_{TMAX}$. The reason is that a device will often not transmit simultaneously on all its configured uplink carriers and the device should then preferably still be able to transmit with the maximum allowed power $P_{TMAX}$. Thus, there may be situations when the sum of the transmit power of each carrier given by the power-control expression (15.1) exceeds $P_{TMAX}$. In that case, the power of each carrier needs to be scaled down to ensure that the eventual transmit power of the device does not exceed the maximum allowed value.

Another situation that needs to be taken care of is the simultaneous uplink transmission of LTE and NR in the case of a device operating in dual-connectivity between LTE and NR. Note that, at least in an initial phase of NR deployment this will be the normal mode-of-operation as the first release of the NR specifications only support non-standalone NR deployments. In this case, the

[3]Note that, in contrast to LTE, at least for NR release 15 there is not simultaneous PUCCH and PUSCH transmission on a carrier, and thus there is at most one physical channel transmitted on an uplink carrier at a given time instant.

transmission on LTE may limit the power available for NR transmission and vice versa. The basic principle is that the LTE transmission has priority, that is the LTE carrier is transmitted with the power given by the LTE uplink power control [28]. The NR transmission can then use whatever power is left up to the power given by the power-control expression (15.1).

The reason for prioritizing LTE over NR is multifold:

- In the specification of NR, including the support for NR/LTE dual connectivity, there has been an aim to as much as possible avoid any impact on the LTE specifications. Imposing restrictions on the LTE power control, due to the simultaneous transmission on NR, would have implied such an impact.
- At least initially, LTE/NR dual-connectivity will have LTE providing the control-plane signaling, that is, LTE is used for the master cell group (MCG). The LTE link is thus more critical in terms of retaining connectivity and it makes sense to priorities that link over the "secondary" NR link.

## 15.2 UPLINK TIMING CONTROL

The NR uplink allows for uplink intracell orthogonality, implying that uplink transmissions received from different devices within a cell do not cause interference to each other. A requirement for this *uplink orthogonality* to hold is that the uplink slot boundaries for a given numerology are (approximately) time aligned at the base station. More specifically, any timing misalignment between received signals should fall within the cyclic prefix. To ensure such receiver-side time alignment, NR includes a mechanism for *transmit-timing advance*. The mechanism is similar to the corresponding mechanism in LTE, the main difference being the use of different timing advance step sizes for different numerologies.

In essence, timing advance is a negative offset, at the device, between the start of a downlink slot as observed by the device and the start of a slot in the uplink. By controlling the offset appropriately for each device, the network can control the timing of the signals received at the base station from the devices. Devices far from the base station encounter a larger propagation delay and therefore need to start their uplink transmissions somewhat in advance, compared to devices closer to the base station, as illustrated in Fig. 15.2. In this specific example, the first device is located close to the base station and experiences a small propagation delay, $T_{P,1}$. Thus, for this device, a small value of the timing advance offset $T_{A,1}$ is sufficient to compensate for the propagation delay and to ensure the correct timing at the base station. However, a larger value of the timing advance is required for the second device, which is located at a larger distance from the base station and thus experiences a larger propagation delay.

The timing-advance value for each device is determined by the network based on measurements on the respective uplink transmissions. Hence, as long as a

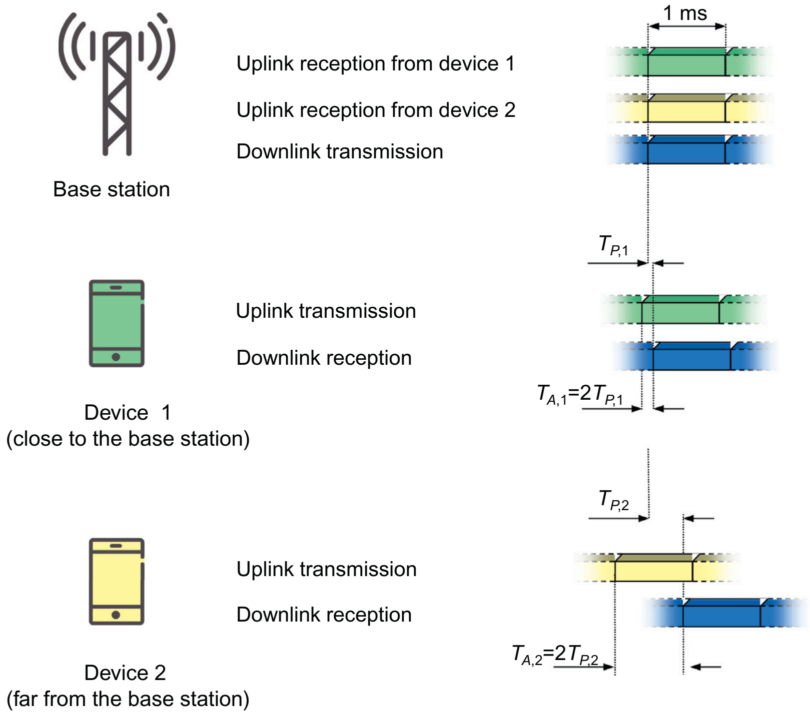


**FIGURE 15.2**

Uplink timing advance.

device carries out uplink data transmission, this can be used by the receiving base station to estimate the uplink receive timing and thus be a source for the timing-advance commands. Sounding reference signals can be used as a regular signal to measure upon, but in principle the base station can use any signal transmitted from the devices.

Based on the uplink measurements, the network determines the required timing correction for each device. If the timing of a specific device needs correction, the network issues a timing-advance command for this specific device, instructing it to retard or advance its timing relative to the current uplink timing. The user-specific timing-advance command is transmitted as a MAC control element on the DL-SCH. Typically, timing-advance commands to a device are transmitted relatively infrequently—for example, one or a few times per second—but obviously this depends on how fast the device is moving.

The procedure described so far is in essence identical to the one used for LTE. As discussed above, the target of timing advance is to keep the timing misalignment within the size of the cyclic prefix and the step size of the timing advance is therefore chosen as a fraction of the cyclic prefix. However, as NR supports multiple numerologies with the cyclic prefix being shorter the higher the subcarrier spacing, the timing advance step size is scaled in proportion to the cyclic prefix length and given by the subcarrier spacing of the active uplink bandwidth part.

If the device has not received a timing-advance command during a (configurable) period, the device assumes it has lost the uplink synchronization. In this case, the device must reestablish uplink timing using the random-access procedure prior to any PUSCH or PUCCH transmission in the uplink.

For carrier aggregation, there may be multiple component carriers transmitted from a single device. A straightforward way of handling this would be to apply the same timing-advance value for all uplink component carriers. However, if different uplink carriers are received at different geographical locations, for example, by using remote radio heads for some carriers but not others, different carriers would need different timing advance values. Dual connectivity with different uplink carriers terminated at different sites is an example when this is relevant. To handle such scenarios, a similar approach as in LTE is taken, namely to group uplink carriers in so-called timing advanced groups (TAGs) and allow for different timing advance commands for different TAGs. All component carriers in the same group are subject to the same timing-advance command. The timing advance step size is determined by the highest subcarriers pacing among the carriers in a timing advance group.