Chapter 13

Physical Uplink Shared Channel (PUSCH) Closed-Loop Power Control for 3G LTE

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13.1 LTE Physical Layer

13.1.1 Multiplexing Schemes

The capabilities of the evolved NodeB (eNodeB) and user equipment (UE) are obviously quite different; thus, the LTE (long-term evolution) physical layer (PHY), downlink (DL) and uplink (UL) are different.

13.1.1.1 Downlink

Orthogonal frequency division multiplexing (OFDM) is selected as the basic modulation scheme because of its robustness in the presence of severe multipath fading. Orthogonal frequency division multiple access (OFDMA) is used as the multiplexing scheme in the downlink.

13.1.1.2 Uplink

LTE uplink requirements differ from downlink in several ways. Power consumption is a key consideration for UE terminals. High peak-to-average power ratio (PAPR) and related loss of efficiency with OFDM signaling are major concerns. As a result, an alternative to OFDMA was sought for use in the LTE uplink.

The LTE PHY uses single-carrier frequency division multiple access (SC-FDMA) as the basic transmission scheme for the uplink. SC-FDMA is a modified form of OFDMA. SC-FDMA has a similar throughput performance and an overall...
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13.1.2 Frame Structure
In an uplink, LTE transmissions are segmented into frames [1]; a frame consists of 10 subframes and a subframe is formed by two slots each 0.5 ms long and consists of seven SC-FDMA symbols. The generic frame structure is shown in Figure 13.1.

13.1.3 Physical Resource Block
In LTE, the physical resource block (PRB) is the smallest element of resource allocation assigned by the base station scheduler. A PRB is defined as a resource of 180 kHz in the frequency domain and 0.5 ms (one time slot) in the time domain. Because the subcarrier spacing is 15 kHz, each PRB consists of 12 subcarriers in the frequency domain, as shown in Figure 13.2.

13.1.4 Reference Signals
In contrast to packet-oriented networks, LTE does not use a PHY preamble to facilitate carrier offset estimate, channel estimation, or timing synchronization. Instead, special reference signals are embedded in the PRBs, as shown in Figure 13.3.

Reference signals are transmitted during the first and fifth OFDM symbols of each time slot and in every sixth subcarrier of each subframe. Reference signal is also used to estimate the path loss using reference symbol received power (RSRP).

13.2 Introduction to Power Control
The uplink transmitter power control is a key radio resource management feature in cellular communication systems. It is usually used to provide an adequate transmit power to the desired signals to achieve the necessary quality, minimizing interference.
To other users in the system and maximizing the battery life of the mobile terminal. To achieve these goals, uplink power control has to adapt to the radio propagation channel conditions, including path loss, shadowing, and fast fading fluctuations while limiting the interference effects from other users, within the cell, and from neighboring cells.

LTE is a project within the Third-Generation Partnership Project (3GPP) that aims at improving the current 3G universal mobile telecommunications system (UMTS) standard to cope with future requirements and to maintain competitiveness in the long term. Hence, the important goals of LTE include achieving higher data rates, reducing latency, improving efficiency, enhancing services, exploiting new spectrum opportunities, improving system capacity and coverage, lowering costs, and better integration with other standards.
In order to meet some of these requirements, SC-FDMA has been chosen as the uplink radio access technology in LTE [2]. SC-FDMA has a low PAPR, which leads to lesser power consumption at the UE.

In a multiuser environment, a number of users share the same radio resources. A consequence of the limited availability of radio channels in the network is that the same channel has to be assigned to many users. Thus, a signal intended for a certain user will reach other users, introduce interference to their connection, and degrade the system quality. A user with very good quality may consider using low power and still having acceptable quality. The advantage is that it will disturb other users less, thereby improving their quality. Power control is essentially doing the same task but in a controlled manner.

Using an orthogonal transmission scheme eliminates mutual interference between users in the same cell (intra-cell interference) and the near-far problem typically encountered in CDMA systems. However, because transmission in the neighboring cell is not orthogonal, there is interference between users in neighboring cells (inter-cell interference), which ultimately limits system performance and capacity.

To maximize the spectral efficiency in LTE, a frequency reuse of 1 is selected for both the downlink and the uplink [2], which means that all cells in the network use the same frequency band. Thus, both data and control channels are sensitive to inter-cell interference. Cell-edge performance and capacity of a cell site can be limited by the inter-cell interference. Therefore, the role of a closed-loop power control becomes decisive because it ensures that the required SINR is maintained at an acceptable level of communication between the eNB and the UE while controlling interference caused to neighboring cells.
In addition, in the coming years, many portable devices (e.g., notebooks, ultraportables, gaming devices, and video cameras) are also expected to operate over mobile broadband technologies such as LTE. The battery power is an important and scarce resource in these devices. Thus, the application of an efficient power control mechanism is crucial in order to minimize the consumption of battery power and use the available resources efficiently.

The foregoing requirements are used in the LTE physical uplink shared channel (PUSCH) power control scheme [2], which is a combination of an open-loop and closed-loop mechanism. The scheme allows for full or partial compensation (of path loss and shadowing) as opposed to the conventional uplink power control scheme (full compensation) in which all users receive the same SINR [3, 4]. The open-loop component compensates for the slow channel variations based on signal strength measurements performed by the terminal, which reduces the power to cell-edge users since they are likely to generate higher interference to others. The closed-loop component, on the other hand, directly controls the terminals power using explicit transmit power control (TPC) commands in the downlink to optimize the system performance. The potential benefit of fractional path loss compensation is a relatively lower transmitted power for terminals closer to the cell border, implying less interference to other cells. However, this also leads to reduce data rates for those terminals.

This chapter presents a novel closed-loop power control algorithm with fractional path loss compensation for the PUSCH for a 3GPP LTE system. In contrast to conventional closed-loop power control, the proposed scheme sets a SINR target for all users based on their path loss, which allows users with good radio conditions to achieve better SINR and, at the same time, providing a better cell-edge bit rate. Different values of the fractional path loss compensation factor (in the range 0.7–1.0) are tested, and an optimal value that provides the best cell-edge performance for a given SINR target is selected for further investigation. Realistic simulation scenarios are modeled by taking into account the mobility, delay, error, and power headroom reporting and performance results compared with the ideal case [5]. Simulation results show that closed-loop power control with a fractional path loss compensation factor is advantageous compared to closed-loop power control with full path loss compensation. Using a simple upload traffic model, the closed-loop power control with a fractional path loss compensation factor improved system performance in terms of mean bit rate by 68% in the ideal case and 63% in the realistic case. In addition, the proposed algorithm provides a better cell-edge bit rate and better battery life performance.

The chapter is organized as follows. In Section 13.3 PUSCH power control formula and basic PUSCH power control signaling is presented. In Section 13.4 we present LTE power control schemes and their comparison based on power spectral density. In Section 13.5, we present a proposed closed-loop power control algorithm, traffic models, and realistic simulation environments. Simulation results are presented in Section 13.6. Finally, Section 13.7 concludes the chapter.
13.3 LTE PUSCH Uplink Power Control

The power control scheme for the physical uplink shared channel (PUSCH) is the combination of an open-loop power control (OLPC) and closed-loop power control (CLPC). The 3GPP specifications [2] define the setting of the UE transmit power for PUSCH by the following equation:

\[
P_{\text{PUSCH}} = \min\{P_{\text{max}}, 10 \cdot \log_{10} M + P_0 + \alpha \times PL + \delta_{\text{mcs}} + f(\Delta_i)\} \text{ [dBm]}
\]

(13.1)

where

- \(P_{\text{max}}\) is the maximum allowed transmit power, which depends on the UE power class;
- \(M\) is the number of physical resource blocks (PRB);
- \(P_0\) is a cell/UE-specific parameter signaled by the radio resource control (RRC). However, we assume that \(P_0\) is cell specific;
- \(\alpha\) is the path loss compensation factor. It is a three-bit cell specific parameter in the range [0, 1] signaled by the RRC;
- \(PL\) is the downlink path loss estimate and is calculated in the UE based on the RSRP;
- \(\delta_{\text{mcs}}\) is a cell/UE-specific modulation and coding scheme parameter defined in the 3GPP specifications for LTE. The setting of \(\delta_{\text{mcs}}\) is beyond the scope of this chapter;
- \(f(\Delta_i)\) is UE specific. \(\Delta_i\) is a closed loop correction value, and \(f\) is a function that permits us to use an accumulated or an absolute correction value.

The parameter \(P_0\) is calculated [6] as follows:

\[
P_0 = \alpha \cdot (SNR_0 + P_n) + (1 - \alpha)(P_{\text{max}} - 10 \cdot \log_{10} M_0) \text{ [dBm]}
\]

(13.2)

where

- \(SNR_0\) is the open-loop target SNR (signal-to-noise ratio);
- \(P_n\) is the noise power per PRB;
- \(M_0\) defines the number of PRBs for which the SNR target is reached with full power. It is set to 1 for simplicity.

13.3.1 PUSCH Power Control Signaling

Many of the parameters listed in Equation 13.1 are broadcasted by the eNB toward the UEs; that is, they are the same for all the users in that specific cell. Figure 13.4 shows the UE parameters (e.g., \(\Delta_i\), \(\alpha\), \(P_0\), and \(\delta_{\text{mcs}}\)) received from the eNB.
13.4 LTE Power Control Schemes

In this section, LTE power control schemes are discussed and different ways of categorizing them are presented.

13.4.1 Power Spectral Density (PSD)

The UE sets its initial transmission power based on parameters received from the eNB and the path loss calculated by the UE. It is worthwhile to note that \( \delta_{\text{i}} \) is signaled by the eNB to any UE after it sets its initial transmit power; that is, \( \delta_{\text{i}} \) has no contribution in the initial setting of the UE transmit power. The expression on which a UE sets its initial power can be obtained from Equation 13.1 by ignoring \( \delta_{\text{mcs}} \) and the closed-loop correction, whereas power limitation can be neglected because we assume that the UE has to take the power limitation into account, and is given by the following:

\[
P_{\text{PUSCH}} = 10 \cdot \log_{10} M + P_0 + \alpha \times \text{PL} \ [\text{dBm}] \quad (13.3)
\]

where \( M \) is the total number of PRB scheduled by the eNB. The power assignment for transmission at the UE is performed on the basis of PRB, and each PRB contains an equal amount of power. Thus, by neglecting \( M \), the expression used by the UE to assign power to each PRB is given by

\[
PSD_{\text{TX}} = P_0 + \alpha \times \text{PL} \ [\text{dBm/PRB}] \quad (13.4)
\]
Equation 13.4 represents the transmit power spectral density (PSD) of a PRB expressed in dBm/PRB. $PSD_{Tx}$ is a helpful way to explain the basic difference between conventional and fractional power control.

The power control scheme can be categorized based on the value of $\alpha$ in Equation 13.4 as follows:

$\alpha = 1$ (full compensation of path loss), which is the well-known conventional power control scheme,

$0 < \alpha < 1$ (fractional compensation of path loss) turns to fractional power control,

$\alpha = 0$ (no compensation of path loss) leads to no power control; that is, all users will use the maximum allowed transmission power ($P_{\text{max}}$).

### 13.4.2 Conventional Power Control Scheme

If full compensation of path loss is used ($\alpha = 1$), then $P_0$ is given as

$$P_0 = SNR_0 + P_n \text{ [dBm]} \quad (13.5)$$

The $PSD_{Tx}$ is thus defined as follows:

$$PSD_{Tx} = P_0 + PL = SNR_0 P_n + PL \text{ [dBm/PRB]} \quad (13.6)$$

Taking the path loss into account, the received PSD at the eNB is then given by

$$PSD_{Rx} = (SNR_0 + P_n) = P_0 \text{ [dBm/PRB]} \quad (13.7)$$

It is clear from Equation 13.7 that the received PSD at the eNB is equal to $P_0$, thus, this equation illustrates that the conventional power control scheme steers all users with equal power spectral density. This scheme is widely used in cellular systems that are not using orthogonal transmission scheme in the uplink, such as conventional CDMA-based systems. One of the advantages of this power control scheme is that it removes the near-far problem typically experienced by CDMA systems, as it equalizes power of all UEs received at the base station. Figure 13.5 shows the received PSD for users as a function of path loss. It can be clearly seen that, for a given SNR target, the received PSD is same for all users independent of their path loss. It is worthwhile to note that the “knee point” indicates the power limited region where users at this point and beyond will start to use $P_{\text{max}}$; in other words, it shows the maximum path loss that results in uplink power equal to $P_{\text{max}}$ by the user. The knee point drifts to the left by increasing the SNR target ($SNR_0$); this means that users will be power limited more quickly. High $SNR_0$ mostly favors users close to the eNB, whereas a lower $SNR_0$ favors users at the cells’ edge.
13.4.3 Fractional Power Control Scheme

The fractional power control (FPC) scheme allows users to receive variable PSDs, depending on their path loss; that is, the user with good radio conditions will receive high PSD and vice versa. Using \( 0 < \alpha < 1 \), the PSD is given by

\[
\text{PSD}_{\text{Tx}} = P_0 + \alpha PL = \alpha \cdot (\text{SNR}_0 + P_n) + (1 - \alpha)(P_{\text{max}}) + \alpha PL \quad [\text{dBm/PRB}]
\]  

(13.8)

In contrast to conventional power control, which allows full compensation of path loss, FPC compensates only for a fraction of the path loss, hence the name. The PSD received can be found by taking the path loss into account and is given by

\[
\text{PSD}_{\text{Rx}} = P_0 + PL(\alpha - 1) \quad [\text{dBm/PRB}]
\]  

(13.9)

Attention is drawn here by comparing Equations 13.7 and 13.9 where the received PSD in a conventional power control scheme results in \( P_0 \), whereas in case of the FPC scheme it also has an additional term \( PL(\alpha - 1) \). Because both \( P_0 \) and \( \alpha \) are cell-specific parameters broadcast toward UEs by the eNB (same for all the UEs), then PL is the key factor in Equation 13.9 that allows users to be received with different power spectral densities. This observation can be explained by plotting Equation 13.9 as a function of the path loss (Figure 13.6). This figure clearly shows that, for the FPC scheme \( 0 < \alpha < 1 \), the users receive variable PSDs,
depending on their path loss. The conventional or full compensation ($\alpha = 1$) and no compensation ($\alpha = 0$) power control schemes are also shown as benchmarks in this figure. Also notice that the knee point drifts toward the left by decreasing $\alpha$ and/or increasing $SNR_0$.

In Figure 13.6, $\alpha = 1$ (full compensation) and $\alpha = 0$ (no compensation) shows the conventional and no power control scheme, respectively; for $0 < \alpha < 1$ is the fractional setting where users are received with variable PSD depending on their path loss. The “knee point” drifts towards left by decreasing $\alpha$ and/or increasing $SNR_0$.

### 13.4.4 Slope of the Received PSD

In Section 13.4.1, the power control schemes are categorized based on the path loss compensation factor. However, the slope of the received PSD is another way of categorizing the different power control algorithms.

Figure 13.7 shows different slopes of the received PSD for various values of $\alpha (0 \leq \alpha \leq 1)$. For FPC ($0 < \alpha < 1$), the slope is $\alpha - 1$. If $\alpha = 0$, the slope is $-1$, which implies no power control, whereas if $\alpha = 1$ results in slope $= 0$, which leads to conventional open-loop power control. The figure also defines the region where users start using the maximum allowed power as identified by the knee point. At the knee point and beyond, users will experience maximum path loss, which results in using maximum power. The received PSD for the fractional power control is shown...
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Figure 13.7 Illustration of the relationship between the received PSD and the path loss, describing the slopes for different power control algorithms.

by the solid line, and the received PSD for the conventional and no-power control schemes are shown by the dashed lines. For conventional open-loop power control, the received PSD is same for all the UEs, independent of their path loss as shown in Figure 13.7.

It is worthwhile to note that, conventional and fractional power control indicates the choice of value for $\alpha$, whereas open-loop and closed-loop power control indicates the method of setting the UEs’ transmission power.

13.4.5 Open-Loop Power Control

Open-loop power control is the means by which the UE transmitter is able to set its uplink transmit power to a specified value suitable for receiver operation. This setting, discussed in Section 13.4.1 is based on Equation 13.3, thus the uplink power ($P_{OL}$) set by the open-loop power controller can be written as follows:

$$P_{OL} = \min(P_{\max}, 10 \cdot \log_{10} M + P_0 + \alpha \cdot PL) \text{ [dBm]}$$ (13.10)

The choice of $\alpha$ depends on whether a conventional or FPC scheme is used. Using $\alpha = 1$ leads to a conventional open-loop power control scheme, whereas $0 < \alpha < 1$ leads to fractional open-loop power control.

Figure 13.8 is a block diagram of the steps involved in setting the uplink transmit power using open-loop power control. An estimate of the path loss is obtained after measuring the reference symbol received power (RSRP). The calculation for transmission power is performed using Equation 13.10. The transmit block in the eNB represents the broadcast of parameters ($P_0$ and $\alpha$) used in Equation 13.10.
13.4.6 Closed-Loop Power Control

Closed-loop power control is the ability of the UE to adjust the uplink transmit power in accordance with the closed-loop correction values, which is also known as transmit power control (TPC) commands. The TPC commands transmitted by the eNB toward the UE are based on the closed-loop SINR target and the measured received SINR.

In an LTE closed-loop power control system, the uplink receiver at the eNB estimates the SINR of the received signal and compares it with the desired SINR target value. If the received SINR is below the SINR target, a TPC command is transmitted to the UE to request for an increase in the transmitter power. Otherwise, the TPC command will request for a decrease in transmitter power.

The LTE closed-loop power control mechanism operates around an open-loop point of operation. As discussed in Section 13.4.1, the UE adjusts its uplink
transmission power based on the TPC commands it receives from the eNB when the uplink power setting is performed at the UE using open-loop power control. The closed-loop power control mechanism around open-loop point of operation is presented in Figure 13.9. The shaded blocks indicate the closed-loop power control components. It can be seen in Figure 13.9 that the closed-loop correction value is applied after calculating the transmission power using the open-loop power control. The PUSCH closed-loop power control expression is given by:

\[
P_{\text{PUSCH}} = \min\{P_{\text{max}}, P_{\text{OL}} + f(\Delta_i)\} \text{ [dBm]} \tag{13.11}
\]

Figure 13.9  Block diagram of steps involved in adjusting the open-loop point of operation using the closed-loop power control.
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Figure 13.10 Generation of the TPC command at the eNB.

It is worthwhile to note that, if $P_{\text{PUSCH}}$ is set using the closed-loop power control, power limitation is neglected in Equation 13.10 and is applied by Equation 13.11. In case of the conventional closed-loop power control, the open-loop component uses $\alpha = 1$. $f(\Delta_i)$ is the closed-loop adjustment to the open-loop point of operation and is defined as [2]

$$f(i) = f(i - 1) + \delta_{\text{PUSCH}}(i - K_{\text{PUSCH}}) \text{ [dB]}$$

(13.12)

where $\delta_{\text{PUSCH}}$ is the UE specific correction value, which is also referred as the TPC command. TPC commands $[-1, 0, 1, 3]$ dB are used during the simulations. Here, $f^{(*)}$ represents accumulation and $f(0) = 0$ and $K_{\text{PUSCH}} = 4$ TTI (transmission time intervals). $K_{\text{PUSCH}}$ includes both processing and round-trip propagation time delay; this issue is discussed in Section 13.5.3. TPC commands are generated based on the difference between the SINR target and the received SINR, as shown in Figure 13.10.

The mapping function maps the resulting difference to one of the accumulated TPC commands. The generated TPC commands are transmitted by the eNB toward the UE. In this chapter, the conventional closed-loop SINR target is used in generating TPC commands, which is referred to as the baseline SINR target.

13.5 Proposed Closed-Loop Power Control Algorithm

In this section, a novel fractional closed-loop power control algorithm is presented and analyzed using different traffic models and realistic simulation scenarios. In addition, its performance is compared to that of a conventional closed-loop power control and open-loop power control algorithms.

The conventional closed-loop power control scheme steers all users to achieve equal received SINR, as seen in Figure 13.11. Consequently, users with good radio conditions (i.e., good channel quality) that possibly can achieve high received SINR are affected by this setting, thus resulting in a lower mean user bit rate. On the other hand, if we look at the open-loop power control performance, we see that users experiencing good radio conditions achieve high received SINR, but the cell-edge performance is worse compared to that of the conventional closed loop.
In conventional closed-loop power control, the SINR target setting is the same for all users and is a trade-off between the cell-edge rate and the mean bit rate; that is, a high SINR target results in high mean user bit rate but a lower cell-edge bit rate, whereas a lower SINR target leads to a low mean and a high cell-edge bit rate.

It is desirable to design a closed-loop power control scheme that can provide a reasonable cell-edge bit rate and, at the same time, allow users with good radio conditions to achieve high received SINR, and subsequently attaining high mean user bit rate. In the following sections, we present a novel fractional closed-loop power control scheme that achieves these goals. In contrast to conventional closed-loop power control, the proposed scheme sets an SINR target for each user based on their path loss, which allows users with good radio conditions to achieve better SINR and, at the same time, provide a better cell-edge bit rate. In Section 13.5.2, setting an SINR target based on users’ path loss is discussed and its mathematical expression is derived.

### 13.5.1 Power Headroom Report

Power headroom ($P_h$) is a mechanism by which the mobile terminal is configured to provide regular reports on its power to the network. The power headroom report can be used by the eNB to calculate the path loss of the users which is then used in setting of SINR target. Power headroom report is sent by the UE to the eNB which indicates how much power UE is left with to start using full power. In other words,
it is the difference between the UE transmit power and the maximum UE transmit power and is given by

\[ P_b = P_{\text{max}} - P_{\text{PUSCH}} \text{ [dBm]} \] (13.13)

The following triggers [7] should apply to power headroom reporting:

- The path loss has changed by a threshold value, as the last power headroom report is sent. The threshold value can be \([1, 3, 6, \infty]\) dB.
- The time elapsed from previous power headroom report is more than \(Y\) transmission time intervals (TTIs). The parameter \(Y\) can take values \([10, 20, 50, 200, 1000, \infty]\) TTIs.
- A power headroom report can only be sent when the UE has an UL grant. If one or several triggers are fulfilled when the UE does not have a grant, the UE should send the report when it has a grant again.

### 13.5.2 Mathematical Model for Setting an SINR Target Based on Path Loss of the Users

A mathematical expression needs to be derived to set the closed-loop SINR target based on the path loss of users while keeping the baseline SINR target for those users that are using full power \((P_{\text{max}})\). Therefore, a relation is formed between the received SINR and path loss (PL) of the users with the aid of an illustration shown in Figure 13.12. In the figure, \(PL_{\text{max}}\) is the maximum path loss, at which users start using \(P_{\text{PUSCH}} = P_{\text{max}}\). \(PL < PL_{\text{max}}\) is the path loss of any arbitrary user, and \(\text{SINR}_{\text{target}}\) is the closed-loop baseline SINR target to start with. \(\text{SINR}_{\text{target}}\) is the SINR target based on the path loss and \(\alpha\) is the path loss compensation factor, whereas \(m\) is the slope and is given by \(\alpha - 1\), and \(IN\) is the interference and noise power in dBm. The knee point in Figure 13.12 is denoted by \(PL_{\text{max}}\) where users use \(P_{\text{max}}\) at this point and beyond. The users at \(PL < PL_{\text{max}}\) are experiencing relatively better radio conditions than users at \(PL \geq PL_{\text{max}}\), and it is desirable that users should take advantage of good radio conditions.

Using Figure 13.12 and the information discussed above, the required mathematical equation that provides an SINR target based on the path loss of users can be obtained using the slope of the line and is given by

\[ m = \frac{\Delta Y}{\Delta X} \] (13.14)

where

\[ \Delta Y = \text{SINR}_{\text{target}}' - \text{SINR}_{\text{target}} \text{ [dB]} \] (13.15)

\[ \Delta X = PL - PL_{\text{max}} \text{ [dB]} \] (13.16)
By using Equation 13.1, $PL$ can be defined as

$$PL = \left\lfloor \frac{1}{\alpha \cdot \{P_{\text{PUSCH}} - 10 \cdot \log_{10} M - P_0 - f(\Delta_t)} \right\rfloor \text{[dB]} \quad (13.17)$$

$PL$ involves $P_{\text{PUSCH}}$, as can be clearly seen in Equation 13.17. In the real world, however, the eNB can use the power headroom report ($P_h$) received by the eNB from the UE to find the path loss of each user. Thus, $PL$ can be rewritten as

$$PL = \left\lfloor \frac{1}{\alpha \cdot \{P_h - 10 \cdot \log_{10} M - P_0 - f(\Delta_t)} \right\rfloor \text{[dB]} \quad \text{when} \quad PL = PL_{\text{max}}.$$

By using Equations 13.13 through 13.17, the SINR target based on the path loss is given by

$$\text{SINR target'} = \begin{cases} (\alpha - 1) \cdot (PL - PL_{\text{max}}) + \text{SINR target} & PL < PL_{\text{max}} \\ \text{SINR target} & PL \geq PL_{\text{max}} \end{cases} \text{[dB]} \quad (13.19)$$

In Equation 13.18, users at $PL \geq PL_{\text{max}}$ will use $\text{SINR target'} = \text{SINR target}$, indicating that there is no increase in the SINR target for users that are already using $P_{\text{PUSCH}} = P_{\text{max}}$. Furthermore, $\alpha = 1$ turns the designed closed loop scheme into conventional closed-loop power control implying that the SINR target setting is independent of the path loss.
In the case of a closed loop with fractional path loss compensation factor, TPC commands will be generated based on the \( \text{SINR}_{\text{target}} \) and the received SINR. The closed-loop power control combined with fractional path loss compensation factor can be implemented using Equation 13.11 which defines the basic expression for the closed-loop power control. However, in contrast to conventional closed-loop implementation, which uses a baseline SINR target (same for all users) and \( \alpha = 1 \), a closed loop with fractional path loss compensation factor implementation involves an SINR target setting based on the path loss of the users and \( 0 < \alpha < 1 \).

### 13.5.3 Processing and Round-Trip Time Delay Model

The eNodeB issues a TPC command to adjust the power at the UE. However, the adjustment takes place after some delay. This delay is typically propagation round-trip time (RTT) and processing time at the UE and the eNB. The RTT delay is due to the wave propagation, while the processing delay at the eNodeB occurs due to measuring the received SINR and issue of TPC command based on SINR target and received SINR. The processing delay at the UE occurs due to measuring the RSRP, calculating the \( PL \), calculating the transmit power, and applying the adjustment based on the received TPC command. The total time delay used during simulations is of 4 ms. The time delay is demonstrated with the help of Figure 13.13. In the figure, \( T_{UL} - T_{DL} \) is the difference between the duration of the UL and DL subframe. \( T_p \) is the propagation time, and the round-trip propagation time is \( 2 \times T_p \). We assume that the eNB received the first transmission from the UE; the TPC command is generated based on the difference between the SINR target and the received SINR measured at the eNB.

![Figure 13.13 Illustration of time delay.](image-url)
At time instant $t = 0$, the eNB sent the TPC command that was received by the UE after a delay equal to half of the propagation RTT (i.e., $T_p/2$). Processing time at the UE is 3 ms–propagation RTT [8]. Thus, the UE have to adjust the power and transmit half of the propagation time before $t = 4$. The power-adjusted transmission is received by the eNB at $t = 4$. The received transmission is decoded and a new TPC command is generated at $t = 5$. This makes a total time delay of 4 TTI.

As a consequence of four time instant delays, the eNB must take into account previous TPC commands while issuing a new TPC command. Let us say that the UE power needs to be adjusted by a single TPC command of $+1$ dB and is issued by the eNB at time instant $t = 0$. Now, until time instant $t = 5$, the eNB will receive a transmission without closed-loop adjustment; if the eNB continues issuing TPC commands independent of previously issued TPC commands, UE will end up at $+4$ dB more in $P_{PUSCH}$. In order to prevent this phenomenon, the sum of previously issued TPC commands are fed back to the mapping function, as illustrated in Figure 13.14. Thus, new TPC commands will be generated based on the SINR target, the estimated received SINR, and previously issued TPC commands. Now, as previously, issued commands are taken into account by the eNB between $t = 1$ and $t = 5$. The TPC command of 0 dB will be transmitted toward the UE.

**13.5.4 Absolute Open-Loop Error Model**

Open-loop power control errors are usually the result of several factors, such as the accuracy of measurements of the RSRP at the UE and inaccuracies in the radio parts such as temperature sensitivity and tolerances in the standard. The open-loop error is identified as a slowly varying component and varies between manufactures of UEs. Sources of open-loop power control error are illustrated in Figure 13.15.

![Figure 13.14](image)

**Figure 13.14** Generation of TPC commands at the eNB, taking into account previously issued TPC commands.
At the time of writing, 3GPP had not yet standardized a tolerance in the standard, but because LTE RF components are the same as those used in wideband code division multiple access (WCDMA), the tolerance described in technical specification [4] can be used for first approximation. A tolerance of ±9 dB is required; however, a batch of UEs can handle ±4 dB. Thus, the absolute value of ±4dB with a uniform distribution is considered to be an open-loop error to evaluate the effect of the closed-loop power correction using TPC commands. By taking the absolute open-loop error into account, the expression for the closed-loop power control combined with fraction path loss compensation can be written as

\[ P_{\text{PUSCH}} = \min\{P_{\text{max}}, P_{\text{OL}} + \text{abserr} + f(\Delta_i)\} \text{ [dBm]} \]  

where abserr is the absolute open-loop error.

13.6 Simulation Environment and Results

In this section, we present the simulation environment, the traffic models used, and the associated simulation results. The simulations are carried out using a multicell radio network dynamic simulator implemented in MATLAB. The simulator includes enhanced traffic and hybrid ARQ (HARQ) models. In the simulator, network performance is simulated for a certain period of time, which then includes events like arrival of new users, departure of users (whose calls are finished), and
users’ movements. The simulator also includes a set of radio resource management (RRM) algorithms such as cell selection, scheduling, link adaptation, and transmit beamforming. The default simulation parameters are given in Table 13.1.

The simulator supports a variety of traffic models. In this chapter, we discuss two traffic models: full buffer and simple upload traffic models. The traffic models are based on Poisson processes of user arrivals. Different arrival intensities may be given for different services.

In the full buffer model, neither user leaves due to hang-up, nor does a new user arrive, as each user buffer is filled with infinite data, and the user will not leave until and unless it transmits all the data.

The simple upload traffic model is designed in such a way that users can have limited data in their buffers; thus, a user leaves when it transmits the data and new

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users are added to the system. This model provides the ease to define the user upload file size and mean bearer bit rate. The mean bearer bit rate, along with the offered cell throughput, defines the total number of users in the system. Moreover, the simple upload buffer model also allows inclusion of the effect of queuing delay when calculating the user bit rate. The queuing delay reflects more realistic results and provides a better scale for performance comparison in choosing the optimal value of $\alpha$. For different values of $\alpha$, the 5th percentile and mean user throughput are calculated by taking the effect of queuing delay into account.

The level of interference varies in both traffic models. However, the interferers are the same in the entire simulation in the case of the full buffer model as opposed to the simple upload traffic model because users neither leave nor arrive in the full buffer traffic model. Thus, the full buffer traffic model does not reflect a realistic scenario; however, it is used to compare the performance of the different power control schemes. In the following, simulation results are based on the simple upload traffic model unless otherwise stated.

13.6.1 Investigation for the Optimal Value of the Path Loss Compensation Factor

First, we investigate the performance of the fractional closed-loop power control for different values of $\alpha$ in terms of cell edge and mean bit rate using the full buffer and the simple upload traffic models, respectively. In addition, the value of $\alpha$, which gives the best cell-edge performance for a given SINR target, will be selected for further investigation.

Figure 13.16 shows the performance of the closed-loop power control system using the full buffer traffic model. This figure shows that using $\alpha = 1$ results in a high cell-edge but a relatively low mean bit rate as compared to other values, as the system is less loaded in terms of bits. On the other hand, when using $\alpha = 0.7$ and $0.8$, the user mean bit rate is relatively high, implying that users transmit more bits making the system more loaded, which may lead to a rise in the interference level and a lower cell-edge bit rate than $\alpha = 1$ is achieved. We can also see in Figure 13.16 that the optimal value for $\alpha$ cannot be chosen using the full buffer.

Using a realistic traffic model (i.e., the simple upload traffic model in our scenario), results in a high mean bit rate, which is advantageous, as users can upload (transmit) their data more quickly than a system with low mean bit rate, and users can leave the system early.

In contrast to the full buffer traffic model, Figure 13.17 shows that $\alpha = 1$ results in a low cell-edge bit rate as compared to $\alpha = 0.8$ in the simple upload traffic model. This is because of the relatively high interference, as more users are staying in the system for a longer time. Users stay longer because they cannot transmit their data quickly due to the low mean bit rate. It is evident from Figure 13.17 that the closed loop with full compensation results in a lower mean bit rate. The longer the users
Figure 13.16 Investigating cell-edge and mean bit rate for different values of $\alpha$ for the closed-loop power control using full buffer model.

Figure 13.17 Investigating cell-edge and mean bit rate for different values of $\alpha$ for the closed-loop power control using the simple upload traffic model.
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It is worthwhile to note that, at the end of the simulation, the number of active users using $\alpha = 1$ was 2.6% more than the active users using $\alpha = 0.8$, keeping in view that for each value of $\alpha$ the simulation started with an equal number of users and lasted for an equal amount of time. This implies that due to the high queuing delay using $\alpha = 1$, 2.6% more users could not transmit all the data in their buffer.

Reiterating, and referring to Figure 13.17, compare the performance of $\alpha = 0.8$, 0.7, and 1, we can see that $\alpha = 0.8$ results in a high bit rate both in the cell edge and the mean. Therefore, $\alpha = 0.8$ is a better value for a fractional path loss compensation factor, as it results in the best cell edge and better mean bit rate.

13.6.2 Performance Analysis of the Closed-Loop PC Using $\alpha = 0.8$

In this section, we investigate the performance of the fractional closed-loop power control with the optimal value $\alpha = 0.8$, with the help of the cumulative distribution function (CDF) plots of the user bit rate and uplink-received SINR. The performance evaluation is carried out for both the ideal and realistic scenarios. In the realistic scenario, the time delay, absolute error, and power headroom reporting are taken into account, whereas in the ideal case they are not considered. The full compensation power control algorithm is also shown as a benchmark for comparison purposes.

13.6.3 Ideal Case

It is worthwhile to note that, in this study, calculating $PL$ using Equation 13.16, assuming that $K_{\text{PUSCH}} = 0$ TTI, and taking into account $\text{abserr} = 0$, leads to an ideal study of the closed-loop power control with fractional path loss compensation factor. For a realistic study, $PL$ is calculated using Equation 13.17, which involves power headroom reporting, $K_{\text{PUSCH}} = 4$ TTI is assumed, and an $\text{abserr}$ of $\pm 4$ dB with uniform distribution is considered.

Figure 13.18 shows the performance gain of the closed-loop power control using $\alpha = 0.8$ in both the mean and cell-edge bit rates. The mean bit rate is improved by 68% and provides better cell-edge performance than $\alpha = 1$ at the same time.

Figure 13.19 shows CDF plots of the uplink average-received SINR using the simple upload traffic model. We can see from this figure that the closed-loop power control with full compensation steers all users to achieve an equal uplink average-received SINR, as seen in both 5th percentile users and users close to the base station (i.e., users with good radio conditions) where all users get equal received SINR, as they all aim to achieve the same baseline SINR target. In contrast to full compensation, the closed-loop power control with fractional compensation keeps the baseline SINR target for the worst users and, at the same time, increases the baseline SINR target based for users with good radio conditions based on their path loss where low path
loss results in a high increase in the SINR target. The effect of SINR target setting based on path loss of the users is clearly evident from Figure 13.19, which shows that the better the radio conditions, the higher is the average received SINR.

### 13.6.4 Performance Analysis with Absolute Error and TPC Delay

Here, the individual and combined effects of the open-loop error and TPC delay are investigated. Figure 13.20 shows that the performance of the user bit rate is improved for the users with good radio conditions when taking the open-loop error into account. This is because of the increase of the uplink power due to the open-loop error for the number of UEs, which results in a high received SINR. Performance in terms of user bit rate is slightly degraded for users in the low-CDF region, as the number of UE cannot satisfy the required SINR due to open-loop error. However, the performance change in terms of bit rate due to absolute error is just the initial phenomenon at the start of simulations (i.e., short simulation time), and will not be visible when simulated for longer time since the closed-loop power control compensates, for the open-loop error, using the TPC commands.

The TPC delay introduces an initial delay of only 4 TTI before the UE starts to use the TPC command it received from the eNB to correct its uplink power. It is worth noting that with round robin scheduling, it takes only 14 TTI before all
Performance comparison in terms of uplink received SINR, SINR target: 1 dB

Figure 13.19 CDF plot of the uplink average received SINR.

Performance comparison with the absolute error

Figure 13.20 Performance comparison in terms of the user bit rate when the absolute error is taken into account.
users start to correct their uplink power using the TPC command. Thus, the effect of the TPC delay is not visible, as Figure 13.21 shows, where the closed-loop power control with TPC delay shows the same performance in terms of cell-edge and mean bit rate as that of the closed loop without TPC delay.

Finally, Figure 13.22 shows the combined effect of both the open-loop error and TPC delay. However, because there is no noticeable effect of TPC delay as discussed above, we can conclude that the effect on the user bit rate shown is due to the open-loop error only. It is also evident from the fact that the results in this figure show a similar trend to those in Figure 13.20.

### 13.6.5 Performance Analysis with the Power Headroom Report

Performance of the closed-loop power control with power headroom reports is analyzed in this section. It is worth mentioning that the power headroom is triggered at both the periodic intervals and change in the path loss by a threshold value. In this simulation, the power headroom report is triggered at periodic intervals only.

A performance comparison in terms of user bit rate of the closed-loop power control with full compensation and $\alpha = 0.8$ with or without the power headroom report is shown in Figure 13.23. It can be seen from this figure that with power headroom reports, the user bit rate is degraded for the users with good radio conditions. The reason for the degradation in the mean bit rate is because the SINR target setting is based on an outdated path loss. The SINR target setting based on path loss aims...

![Performance comparison with the TPC delay](image-url)

**Figure 13.21** CDF plot of user bit rate showing both the closed-loop power control with or without the TPC delay. Total simulation time is 200 ms.
Physical Uplink Shared Channel (PUSCH) Closed-Loop Power Control

![Performance comparison with the absolute error and TPC delay](image1)

**Figure 13.22** Performance comparison in terms of the user bit rate when both the absolute error and the TPC delay is taken into account.

![Performance with the Phr report triggering at periodic intervals](image2)

**Figure 13.23** CDF plot of the user bit rate. The power headroom report triggers after 50, 100, and 200 TTIs.
to improve performance in terms of bit rate for users with good radio conditions. Thus, the more outdated the path loss, the more will be the degradation in the mean bit rate, as Figure 13.23 shows for high periodicity values. It is worthwhile to note that, for a longer simulation time and setting the power headroom periodicity to infinity, the performance of the SINR target setting based on path loss will be more like that of the absolute target setting.

13.6.6 Performance Analysis with Power Headroom Report, TPC Delay, and Absolute Error

Figure 13.24 shows performance in terms of user bit rate when taking into account the combined effects of absolute error, time delay, and power headroom report triggering at periodic intervals of 200 ms. The figure shows that the closed-loop power control using $\alpha = 0.8$ shows performance gain in both mean and cell-edge bit rate. The mean bit rate is improved by 63% and, at the same time, provides better cell-edge performance compared to $\alpha = 1$.

13.6.7 Power Use

The difference of the mean of the UEs power consumption results in zero, which implies that the overall power utilization is roughly the same using the closed-loop power control with full and fractional compensation, as can be seen in Figure 13.25.

![Performance analysis of closed loop power control schemes](image)

**Figure 13.24** Performance analysis of the closed-loop power control schemes in terms of the user bit rate, taking into account the power headroom report, absolute error, and time delay.
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However, the closed-loop power control using $\alpha = 0.8$ uses battery power more efficiently, as it provides better system performance in terms of cell edge and mean bit rate than the closed-loop power control with full compensation.

### 13.7 Conclusions

In this chapter, a novel fractional closed-loop power control algorithm for LTE system was proposed. The performance evaluation of the proposed algorithm was carried out using a dynamic radio network simulator. Both the ideal and realistic cases were investigated. The realistic case included the performance evaluation by simulating the effects of absolute error of $\pm4$ dB, time delay, and power headroom report. The path loss compensation factor was investigated for the values in the range 0.7 to 1 as proposed by the standards. The closed-loop power control with full compensation was used as a reference for performance comparison. Simulation results have shown that the conventional closed-loop power control can be replaced by the closed-loop power control with fractional compensation, thus improving system performance in terms of the mean and cell-edge bit rate.

In the ideal case, $\alpha = 0.8$ has shown performance gain over $\alpha = 1$ by improving the mean bit rate by 68% and simultaneously providing the same cell-edge bit rate for a given SINR target. The realistic results using $\alpha = 0.8$ have shown that delay has no effect on the performance of a closed-loop power control. Absolute
error has shown performance gain in terms of mean bit rate because of the initial phenomenon of users arriving with high uplink power. However, improvement due to the initial phenomenon will not be prominent when simulated for a longer time. Performance of the closed-loop power control using $\alpha = 0.8$ was simulated with a power headroom report triggering at periodic intervals, which showed performance degradation in the mean bit rate, as an outdated path loss was used in setting the SINR target. In the realistic case, performance in terms of the mean bit rate improved by 63% for a given SINR target and, at the same time, better cell-edge performance was achieved. This shows that a conventional closed-loop power control can be replaced by the proposed closed-loop power control combined with the fractional path loss compensation factor.

References


[8] 3rd Generation Partnership Project, "3GPP TS 25.101 v8.3.0, universal mobile telecommunications system (UMTS); user equipment (UE), radio transmission and reception (FDD) (Release 8),” 2008.
