Chapter 4
LTE Phyiscal Layer

Physical layer of the radio interface is typically the most important argument when different cellular systems have been compared against each other. The physical layer structures naturally relate directly to the achievable performance issues when observing a single link between a terminal station and a base station. For the overall system performance the protocols in the other layers, such as handover protocols, also have a great deal of impact. Naturally it is essential to have low Signal-to-Interference Ratio (SIR) requirements for sufficient link performance with various coding and diversity solutions in the physical layer, since the physical layer defines the fundamental capacity limits. In this chapter, a detailed description of LTE physical layer while focusing on OFDAM technology is given.

4.1 LTE Fundamental Concepts of PHY Layer

The LTE physical layer is based on orthogonal frequency division multiplexing. OFDM is the transmission scheme of choice to enable high-speed data, video, and multimedia communications and is used by a variety of commercial broadband systems, including DSL, WiFi, Digital Video Broadcast-Handheld (DVB-H), and MediaFLO, besides LTE. OFDM is an elegant and efficient scheme for high data rate transmission in a non-line-of-sight or multipath radio environment. In this section, we cover the basics of OFDM and provide an overview of the LTE physical layer.

4.1.1 Single-Carrier Modulation and Channel Equalization

LTE employs mainly OFDM for downlink data transmission and SC-FDMA for uplink transmission. OFDM is a well-known modulation technique, but is rather novel in cellular applications. This is why in this section, we will start discussing briefly how single-carrier systems are equalized and how they are dealing with multipath-induced channel distortion. This will form a point of reference from which OFDM systems can be compared and contrasted.

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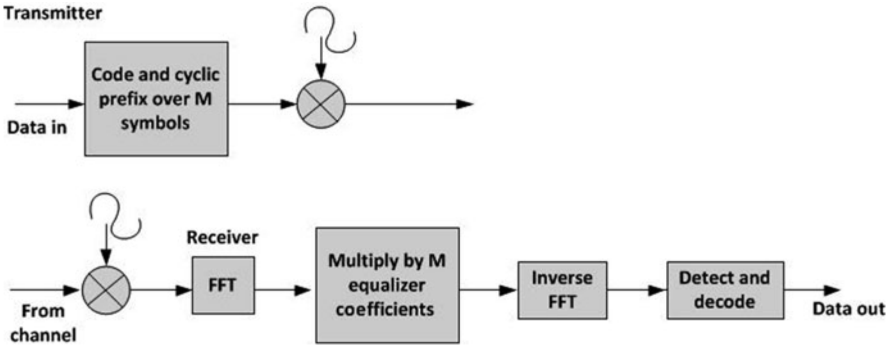

Fig. 4.1 SC-FDE with linear equalization

A single-carrier modulation system is a traditional digital transmission scheme in which data symbols are transported as a fixed symbol rate serial stream of amplitude- and/or phase-modulated pulses, which in turn modulate a sinusoidal carrier. A linear Frequency Domain Equalizer (FDE) performs receiver filtering in the frequency domain to minimize time domain intersymbol interference. Its function is the same as that of a time domain equalizer [1].

Figure 4.1 shows block diagrams of an OFDM system and of a single-carrier system with Frequency Domain Equalization (SC-FDE) and Cyclic Prefix Insertion (CPI). In each of these frequency domain systems, data is organized in blocks, whose length M is typically at least 8–10 times the maximum expected channel impulse response length. In the SC case, the Inverse FFT (IFFT) operation is at the output of the receiver's equalizer. A cyclic prefix, which is a copy of the last part of the transmitted block, is prepended to each block. The length of the cyclic prefix is the maximum expected length of the channel impulse response. In single-carrier receivers, the received cyclic prefix is discarded, and FFT processing is done on each M symbol block.

The cyclic prefix transmitted at the beginning of each block has two main functions: (1) it prevents contamination of a block by Intersymbol Interference (ISI) from the previous block and (2) it makes the received block appear to be periodic with period M (Fig. 4.2). This produces the appearance of circular convolution, which is essential to the proper functioning of the FFT operation. For SC-FDE systems, the cyclic prefix and its consequent overhead requirement can be eliminated by using overlap save processing at the receiver, at the expense of slightly increased complexity [2].

When information is transmitted over a wireless channel, the signal can be distorted due to multipath. Typically there is a line-of-sight path between the transmitter and receiver. In addition, there are many other paths created by signal reflection off buildings, vehicles, and other obstructions as shown in Fig. 4.3. Signals traveling along these paths all reach the receiver, but are shifted in time by an amount corresponding to the differences in the distance traveled along each path.

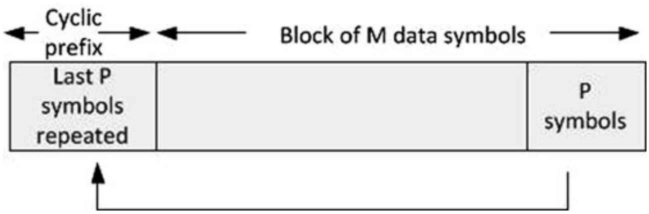

Fig. 4.2 Block processing in frequency domain equalization

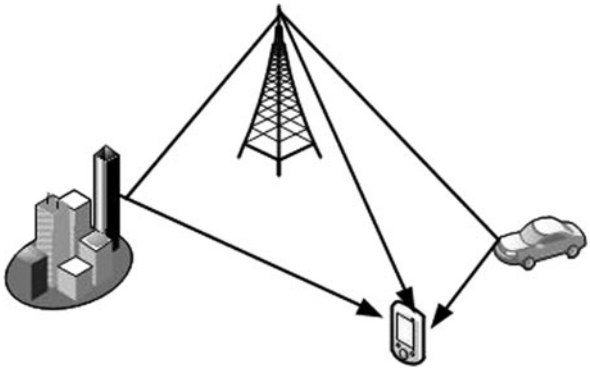

Fig. 4.3 Multipath caused by reflections

The term delay spread describes the amount of time delay at the receiver from a signal traveling from the transmitter along different paths. In cellular applications, delay spreads can be several microseconds. The delay induced by multipath can cause a symbol received along a delayed path to “bleed” into a subsequent symbol arriving at the receiver via a more direct path. This effect is depicted in Figs. 4.4 and 4.5 and is referred to as Inter-Symbol Interference (ISI). In a conventional single-carrier system symbol times decrease as data rates increase. At very high data rates (with correspondingly shorter symbol periods), it is quite possible for ISI to exceed an entire symbol period and spill into a second or third subsequent symbol.

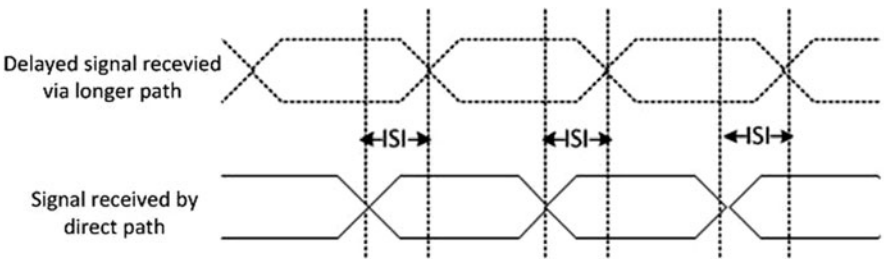

Fig. 4.4 Multipath-induced time delays result in ISI

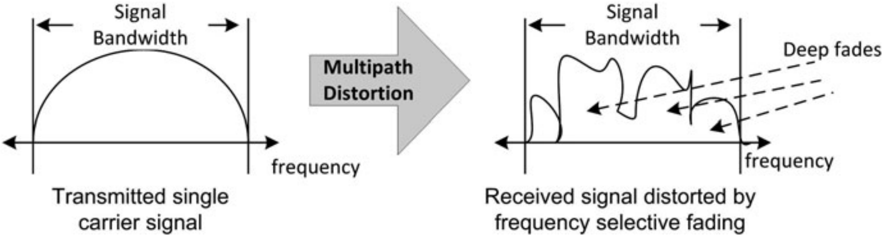

Fig. 4.5 Longer delay spreads result in frequency-selective fading

Generally, time domain equalizers compensate for multipath-induced distortion by one of two methods:

1. Channel inversion: A known sequence is transmitted over the channel prior to sending information. Because the original signal is known at the receiver, a channel equalizer is able to determine the channel response and multiply the subsequent data-bearing signal by the inverse of the channel response to reverse the effects of multipath.
2. CDMA systems can employ rake equalizers to resolve the individual paths and then combine digital copies of the received signal shifted in time to enhance the receiver Signal-to-Noise Ratio (SNR). In either case, channel equalizer implementation becomes increasingly complex as data rates increase. Symbol times become shorter and receiver sample clocks must become correspondingly faster. ISI becomes much more severe – possibly spanning several symbol periods.

The finite impulse response transversal filter (see Fig. 4.6) is a common equalizer topology. As the period of the receiver sample clock (τ) decreases, more samples are required to compensate for a given amount of delay spread. The number of delay taps increases along with the speed and complexity of the adaptive algorithm. For LTE data rates (up to 100 Mbps) and delay spreads (approaching 17 μs), this approach to channel equalization becomes impractical. As we will discuss below, OFDM eliminates ISI in the time domain, which dramatically simplifies the task of channel compensation.

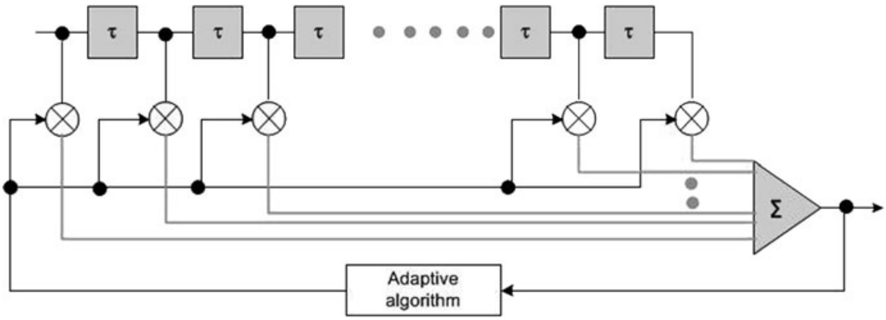

Fig. 4.6 Transversal filter channel equalizer

4.1.2 Frequency Division Multiplexing

Frequency Division Multiplexing (FDM) extends the concept of single-carrier modulation by using multiple subcarriers within the same single channel. The total data rate to be sent in the channel is divided between the various subcarriers. The data does not have to be divided evenly nor does it have to originate from the same information source. Advantages include using separate modulation/demodulation customized to a particular type of data or sending out banks of dissimilar data that can be best sent using multiple, and possibly different, modulation schemes.

FDM offers an advantage over single-carrier modulation in terms of narrow-band frequency interference since this interference will only affect one of the frequency subbands. The other subcarriers will not be affected by the interference. Since each subcarrier has a lower information rate, the data symbol periods in a digital system will be longer, adding some additional immunity to impulse noise and reflections.

FDM systems usually require a guard band between modulated subcarriers to prevent the spectrum of one subcarrier from interfering with another. These guard bands lower the system's effective information rate when compared to a single-carrier system with similar modulation.

4.1.3 OFDM

If the FDM system above had been able to use a set of subcarriers that were orthogonal to each other, a higher level of spectral efficiency could have been achieved. The guardbands that were necessary to allow individual demodulation of subcarriers in an FDM system would no longer be necessary. The use of orthogonal subcarriers would allow the subcarriers' spectra to overlap, thus increasing the spectral efficiency. As long as orthogonality is maintained, it is still possible to recover the individual subcarriers' signals despite their overlapping spectrums.

If the dot product of two deterministic signals is equal to zero, these signals are said to be orthogonal to each other. Orthogonality can also be viewed from the standpoint of stochastic processes. If two random processes are uncorrelated, then they are orthogonal. Given the random nature of signals in a communications system, this probabilistic view of orthogonality provides an intuitive understanding of the implications of orthogonality in OFDM [3].

Recall from signals and systems theory that the sinusoids of the DFT form an orthogonal basis set, and a signal in the vector space of the Discrete Fourier Transform (DFT) can be represented as a linear combination of the orthogonal sinusoids. One view of the DFT is that the transform essentially correlates its input signal with each of the sinusoidal basis functions. If the input signal has some energy at a certain frequency, there will be a peak in the correlation of the input signal and the basis sinusoid that is at that corresponding frequency. This transform is used at the OFDM transmitter to map an input signal onto a set of orthogonal subcarriers, i.e., the orthogonal basis functions of the DFT. Similarly, the transform is used again at the OFDM receiver to process the received subcarriers. The signals from

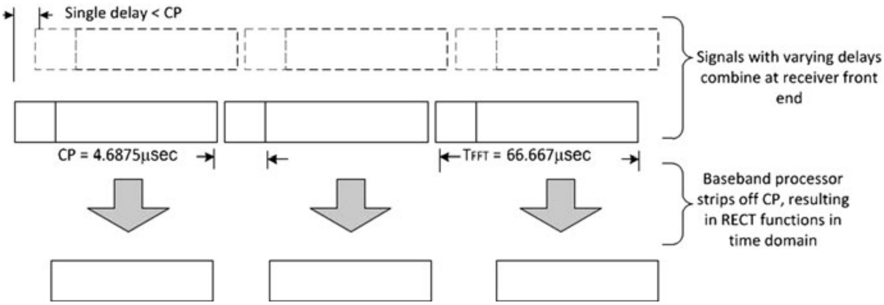

Fig. 4.7 Transversal filter channel equalizer

the subcarriers are then combined to form an estimate of the source signal from the transmitter. The orthogonal and uncorrelated nature of the subcarriers is exploited in OFDM with powerful results. Since the basis functions of the DFT are uncorrelated, the correlation performed in the DFT for a given subcarrier only sees energy for that corresponding subcarrier. The energy from other subcarriers does not contribute because it is uncorrelated. This separation of signal energy is the reason that the OFDM subcarriers' spectrums can overlap without causing interference.

To understand how OFDM deals with ISI induced by multipath, consider the time domain representation of an OFDM symbol shown in Fig. 4.7. The OFDM symbol consists of two major components: the CP and an FFT period (TFFT). The duration of the CP is determined by the highest anticipated degree of delay spread for the targeted application. When transmitted signals arrive at the receiver by two paths of differing length, they are staggered in time as shown in Fig. 4.7.

Within the CP, it is possible to have distortion from the preceding symbol. However, with a CP of sufficient duration, preceding symbols do not spill over into the FFT period; there is only interference caused by time-staggered "copies" of the current symbol. Once the channel impulse response is determined (by periodic transmission of known reference signals), distortion can be corrected by applying an amplitude and phase shift on a subcarrier-by-subcarrier basis. Note that all of the information of relevance to the receiver is contained within the FFT period. Once the signal is received and digitized, the receiver simply throws away the CP. The result is a rectangular pulse that, within each subcarrier, is of constant amplitude over the FFT period.

The rectangular pulses resulting from decimation of the CP are central to the ability to space subcarriers very closely in frequency without creating ICI. Readers may recall that a uniform rectangular pulse (RECT function) in the time domain results in a sinc function ($\sin(x)/x$) in the frequency domain as shown in Fig. 4.8. The LTE FFT period is 67.77 µs. Note that this is simply the inversion of the carrier spacing ($1/\Delta f$). This results in a sinc pattern in the frequency domain with uniformly spaced zero crossings at 15 kHz intervals – precisely at the center of the adjacent subcarrier. It is therefore possible to sample at the center frequency of each subcarrier while encountering no interference from neighboring subcarriers (zero-ICI) [4].

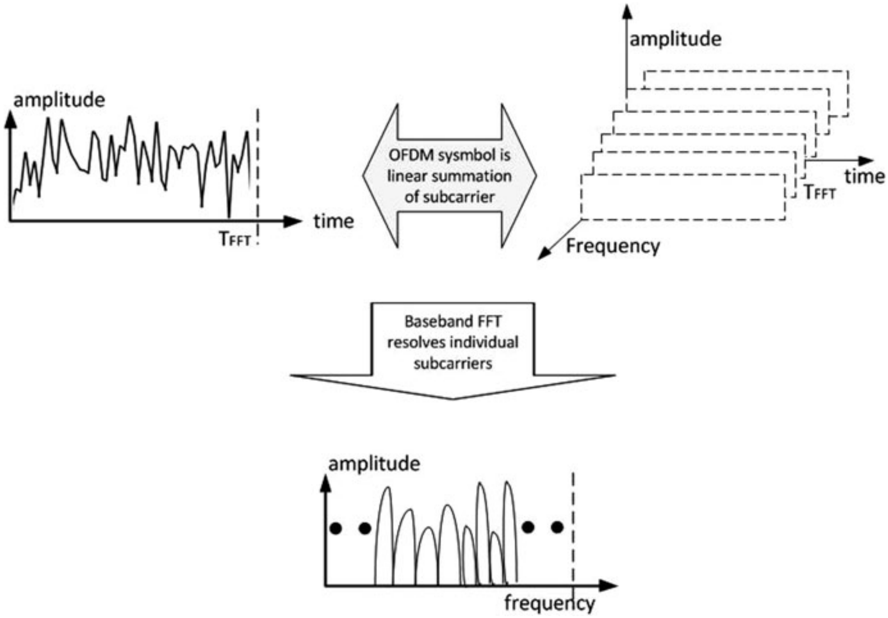

Fig. 4.8 FFT of OFDM symbol reveals distinct subcarriers

4.1.4 Link Adaptation

Uplink link adaptation is used in order to guarantee the required minimum transmission performance of each UE such as the user data rate, packet error rate, and latency, while maximizing the system throughput. For this purpose, uplink link adaptation should effectively utilize a combination of the adaptive transmission bandwidth accompanied with channel-dependent scheduling, transmission power control, and the adaptive modulation and channel coding rate. Three types of link adaptation are performed according to the channel conditions, the UE capability such as the maximum transmission power and maximum transmission bandwidth, and the required QoS such as the data rate, latency, and packet error rate. In particular, the three schemes are controlled by channel variation as link adaptation. The basic features of the three link adaptation methods are as follows:

1. Adaptive transmission bandwidth

    - The transmission bandwidth of each UE is determined at least based on the averaged channel conditions, i.e., path loss and shadowing variation, in addition to the UE capability and required data rate. Furthermore, the adaptive transmission bandwidth based on fast frequency selective fading accompanied with frequency domain channel-dependent scheduling should be investigated during the Study Item phase.

2. Transmission power control

- Transmission power control guarantees the required packet error rate and bit error rate regardless of the channel conditions.
- The target of the received SINR can be different for different UEs in order to increase the system throughput by reducing the inter-cell interference. Thus, the target of the received SINR for the UE at the cell boundary can be smaller than that for the UE in the cell vicinity. The target for the received SINR should also be controlled considering fairness among UEs.

3. Adaptive modulation and channel coding rate

- The adaptive modulation and channel coding rate increase the achievable data rate (frequency efficiency) according to the channel conditions.
- After the transmission bandwidth and transmission power are determined, the adaptive modulation and channel coding rate control selects the appropriate modulation and channel coding rate that maximizes the frequency efficiency while satisfying the required QoS such as the packet error rate and latency.
- The same coding and modulation is applied to all resource units assigned to the same L2 PDU which is mapped on the shared data channel scheduled for a user within a TTI. This applies to both localized and distributed transmission. The overall coding and modulation is illustrated in Fig. 4.9.

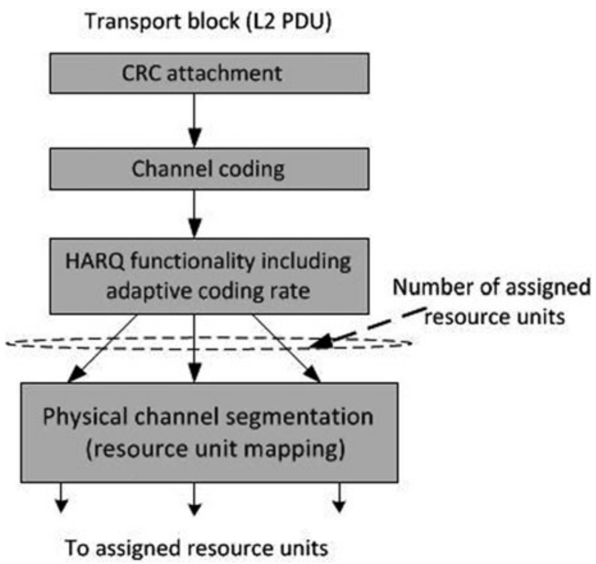

Fig. 4.9 Resource unit-common adaptive modulation and resource unit-common channel coding rate

4.1.5 Generic Radio Frame Structure

The LTE frame structure is shown in Fig. 4.10 where one 10 ms radio frame is comprised of ten 1 ms sub-frames. For FDD, uplink and downlink transmissions are separated in the frequency domain. For TDD, a sub-frame is either allocated to downlink or uplink transmission. Note that for TDD, sub-frame 0 and sub-frame 5 are always allocated for downlink transmission.

Transmitted signal in each slot is described by a resource grid of sub-carriers and available OFDM symbols. Each element in the resource grid is called a resource element and each resource element corresponds to one complex-valued modulation symbol. The number of OFDM symbols per sub-frame is 7 for normal cyclic prefix and 6 for extended cyclic prefix (Fig. 4.11) in the time domain and length of 12 consecutive sub-carriers (180 kHz) in the frequency domain.

The total number of available subcarriers depends on the overall transmission bandwidth of the system. The LTE specifications define parameters for system bandwidths from 1.25 to 20 MHz as shown in Table 4.1. A Physical Resource Block is defined as consisting of 12 consecutive subcarriers for one slot (0.5 ms) in duration. A PRB is the smallest element of resource allocation assigned by the base station scheduler.

The transmitted downlink signal consists of N_{BW} subcarriers for a duration of N_{symb} OFDM symbols. It can be represented by a resource grid as depicted in

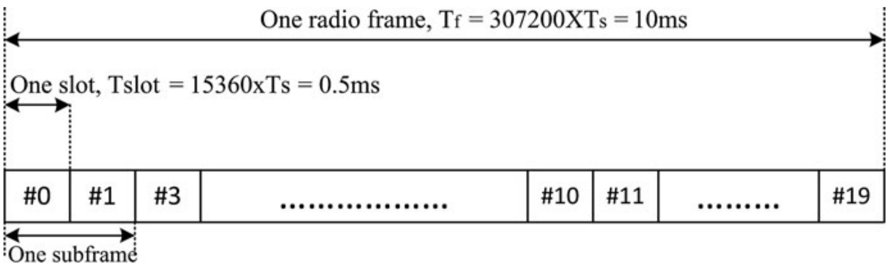

Fig. 4.10 Generic radio frame structure

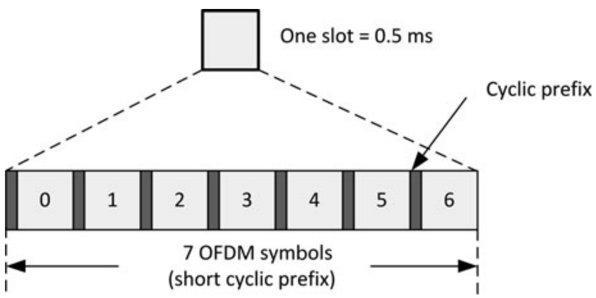

Fig. 4.11 Slot structure

Table 4.1 Downlink OFDM modulation parameters

Parameter	1.4	3	5	10	15	20
Sub-frame duration	1.0 ms					
Subcarrier spacing	15 kHz					
Sampling frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT size	128	256	512	1,024	1,536	2,048
No. of occupied subcarriers	72	180	300	600	900	1,200
CP length normal (μs)	4.69 × 6, 5.21 × 1					
CP length extended (μs)	6.16					

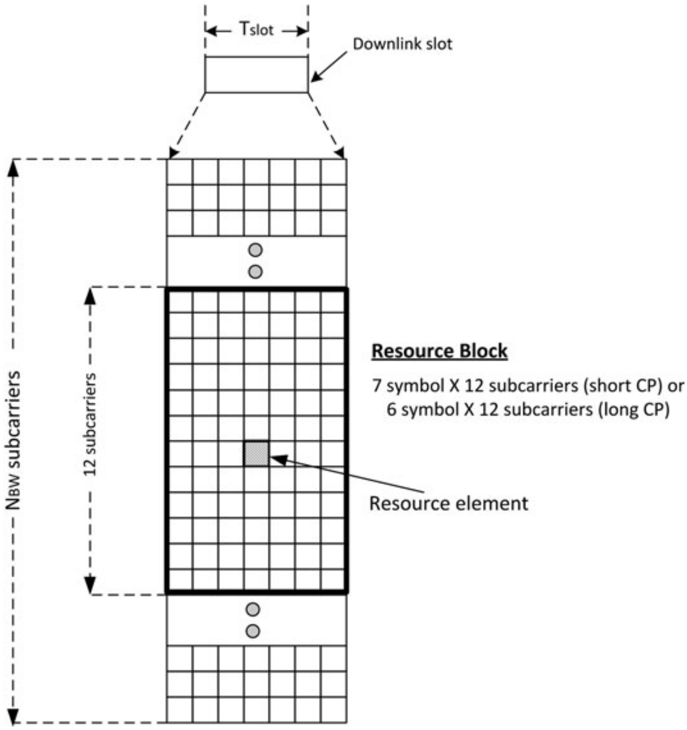

Fig. 4.12 Downlink physical block resources (grids)

Fig. 4.12. Each box within the grid represents a single subcarrier for one symbol period and is referred to as a resource element.

4.1.6 Downlink Reference Signals

To allow for coherent demodulation at the user equipment, reference symbols (or pilot symbols) are inserted in the OFDM time-frequency grid to allow for channel estimation. Downlink reference symbols are inserted within the first and third last OFDM symbol of each slot with a frequency domain spacing of six sub-carriers (this corresponds to the fifth and fourth OFDM symbols of the slot in case of normal and extended cyclic prefix, respectively) as shown in Fig. 4.13 for an LTE system with one antenna in normal CP mode. Furthermore, there is a frequency domain staggering of three sub-carriers between the first and second reference symbols. Therefore, there are four reference symbols within each Resource Block. The user equipment will interpolate over multiple reference symbols to estimate the channel. In case of two transmit antennas, reference signals are inserted from each antenna where the reference signals on the second antenna are offset in the frequency domain by three sub-carriers. To allow the user equipment to accurately estimate the channel coefficients, nothing is transmitted on the other antenna at the same time-frequency location of reference signals.

The reference symbols have complex values, which are determined according to the symbol position as well as of the cell. LTE specifications refer to this as a two-dimensional reference-signal sequence, which indicates the LTE cell identity. There are 510 reference signal sequences corresponding to 510 different cell identities. The reference signals are derived from the product of a two-dimensional pseudo-random sequence and a two-dimensional orthogonal sequence. There are 170 different pseudo-random sequences corresponding to 170 cell identity groups and 3 orthogonal sequences each corresponding to a specific cell identity within the cell identity group.

Reference signals are generated as the product of an orthogonal sequence and a Pseudo-Random Numerical (PRN) sequence. Overall, there are 510 unique reference signals possible. A specified reference signal is assigned to each cell within a network and acts as a cell-specific identifier.

As shown in Fig. 4.13, reference signals are transmitted on equally spaced subcarriers within the first and third last OFDM symbol of each slot. UE must get an accurate CIR from each transmitting antenna. Therefore, when a reference signal is transmitted from one antenna port, the other antenna ports in the cell are idle. Reference signals are sent on every sixth subcarrier. CIR estimates for subcarriers that do not bear reference signals are computed via interpolation. Changing the subcarriers that bear reference signals by pseudo-random frequency hopping is also under consideration.

4.1.7 Uplink Reference Signals

There are two types of reference signals for uplink in LTE. The first is Demodulation Reference Signals (DMRS) which are used to enable coherent signal demodulation at the eNodeB. These signals are time multiplexed with uplink data and are transmitted on the fourth or third SC-FDMA symbol of an uplink slot for normal or extended CP, respectively, using the same bandwidth as the data.

The second is Sounding Reference Signal (SRS) which is used to allow channel-dependent (i.e., frequency-selective) uplink scheduling as the DMRS cannot be used for this purpose since they are assigned over the assigned bandwidth to a UE. The

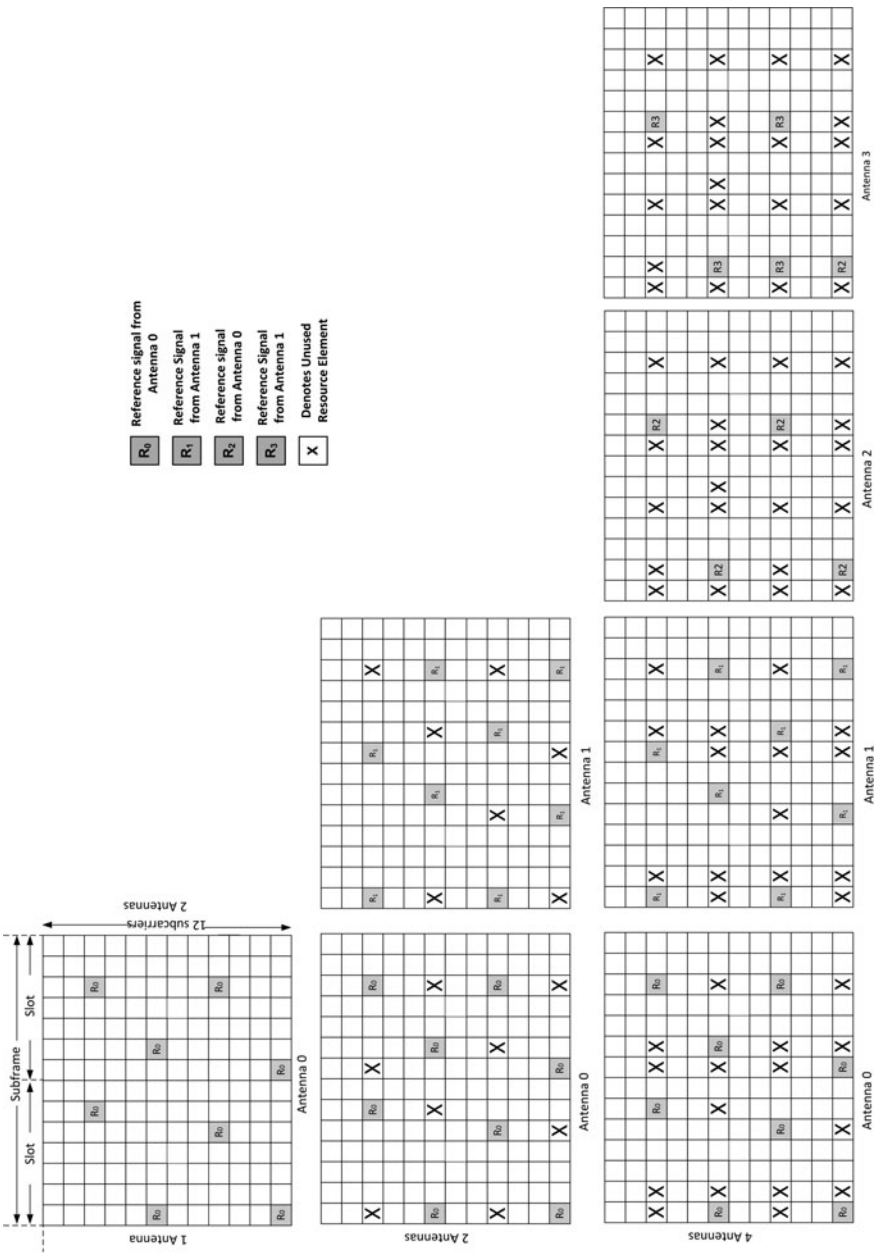

Fig. 4.13 Downlink reference signal

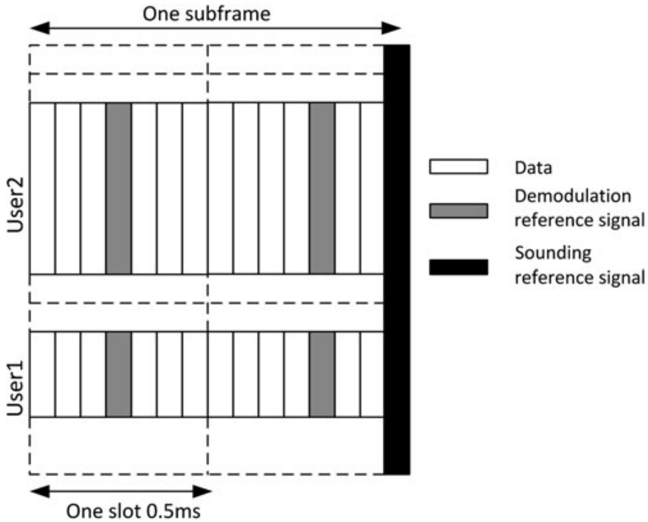

Fig. 4.14 Uplink reference signal

SRS is introduced as a wider band reference signal typically transmitted in the last SC-FDMA symbol of a 1 ms sub-frame as shown in Fig. 4.14. User data transmission is not allowed in this block, which results in about 7% reduction in uplink capacity. The SRS is an optional feature and is highly configurable to control overhead – it can be turned off in a cell. Users with different transmission bandwidth share this sounding channel in the frequency domain.

4.1.8 Downlink Control Channel

Within each downlink sub-frame, downlink control signaling is located in the first n OFDM symbols ($n \leq 3$). There is no mixing of control signaling and shared data in an OFDM symbol. Downlink control signaling consists of format indicator to indicate the number of OFDM symbols used for control in this sub-frame; scheduling control information (downlink assignment and uplink scheduling grant); and downlink ACK/NACK associated with uplink data transmission.

Information fields in the scheduling grants can be divided into distinct categories as follows: control fields containing information related to resource indication such as resource block and duration of assignment; control fields containing information related to the transport format such as multi-antenna information, modulation scheme, and payload size; and control fields containing information related to H-ARQ support such as process number, redundancy version, and new data indicator. For the DL/UL assignment, per-user control channel is used with multiple control channels within each sub-frame. Each control channel carries downlink or uplink scheduling information for one MAC ID; the ID is implicitly encoded in CRC.

For good control channel performance different coding schemes are necessary. As a result, each scheduling grant is defined based on fixed size Control Channel Elements (CCE) which are combined in a predetermined manner to achieve different coding rates. Only QPSK modulation is used so that only a small number of coding formats have to be defined. Because multiple control channel elements can be combined to effectively reduce effective coding rate, a user control channel assignment would then be based on channel quality information reported. A user then monitors a set of candidate control channels which may be configured by higher layer signaling. To minimize the number of blind decoding attempts, 1, 2, 4, and 8 CCEs may be aggregated, resulting in code rates of approx 2/3, 1/3, 1/6, and 1/12.

The downlink acknowledgment comprises of one-bit control information sent in association with uplink data transmission. The resources used for the acknowledgment channel is configured on a semi-static basis and defined independently of the grant channel. Because only one information bit is to be transmitted, CDM multiplexing among acknowledgments is proposed. CDM allows for power control between acknowledgments for different users and provides good interference averaging. However, orthogonality is not maintained in frequency-selective channels for wideband transmission. As a result, a hybrid CDM/FDM scheme (i.e., localized CDM with repetition in different frequency regions) was adopted.

4.1.9 Uplink Control Channel

In E-UTRA, uplink control signaling includes ACK/NACK, CQI, scheduling request indicator, and MIMO codeword feedback. When users have simultaneous uplink data and control transmission, control signaling is multiplexed with data prior to the DFT to preserve the single-carrier property in uplink transmission. In the absence of uplink data transmission, this control signaling is transmitted in a reserved frequency region on the band edge as shown in Fig. 4.15. Note that additional control regions may be defined as needed [5].

Allocation of control channels with their small occupied bandwidth to carrier band edge resource blocks reduces out of carrier band emissions caused by data

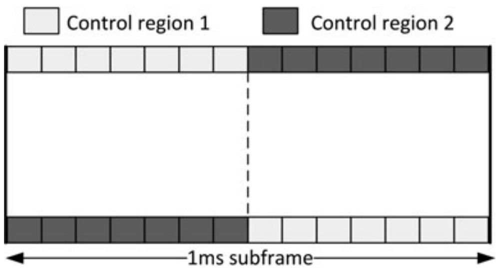

Fig. 4.15 Uplink control signal

resource allocations on inner band resource blocks and maximizes the frequency diversity benefit for frequency diverse control channel allocations while preserving the single-carrier property of the uplink waveform. This FDM allocation of control resources to outer carrier band edge allows an increase in the maximum power level as well as maximizes the assignable uplink data rate since inserting control regions with consecutive sub-carriers in the central portion of a carrier band requires that the time and frequency resources on either side of the control region be assigned to different UEs.

4.2 MIMO and LTE

LTE Release 8 (Rel-8) supports downlink transmissions on one, two, or four cell-specific antenna ports, each corresponding to one, two, or four cell-specific reference signals, where each reference signal corresponds to one antenna port. An additional antenna port, associated with one UE-specific reference signal, is available as well. This antenna port can be used for conventional beamforming, especially in case of TDD operation. An overview of the multi-antenna-related processing including parts of the UE is given in Fig. 4.16. All bit-level processing (i.e., up to and including the scrambling module) for the n^th transport block in a certain sub-frame is denoted codeword n. Up to two transport blocks can be transmitted simultaneously, while up to $Q = 4$ layers can be transmitted for the rank-four case so there is a need to map the codewords (transport blocks) to the appropriate layer. Using fewer transport blocks than layers serves to save signaling overhead as the HARQ-associated signaling is rather expensive. The layers form a sequence of $Q \times 1$ symbol vectors:

$$S_n = [S_{n,1}\ S_{n,2} \ldots S_{n,Q}]^T \tag{4.1}$$

which are input to a precoder that in general can be modeled in the form of a linear dispersion encoder. From a standard point of view, the precoder only exists if the PDSCH (Physical Downlink Shared CHannel) is configured to use cell-specific reference signals, which are then added after the precoding and thus do not undergo any precoding. If the PDSCH is configured to use the UE-specific reference signal, which would then also undergo the same precoder operation as the resource

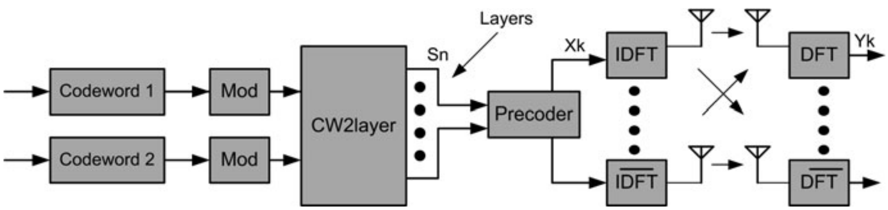

Fig. 4.16 Overview of multi-antenna-related processing in LTE

elements for data, then the precoder operation is transparent to the standard and therefore purely an eNB implementation issue.

The precoder is block based and outputs a block

$$\mathbf{X}_n = [\mathbf{x}_{nL}\ \mathbf{x}_{nL+1} \ldots \mathbf{x}_{nL+L-1}] \tag{4.2}$$

of precoded $N_{T\times 1}$ vectors for every symbol vector s_n. The parameter N_T corresponds to the number of antenna ports if PDSCH is configured to use cell-specific reference signals. If a transmission mode using UE-specific reference signals is configured, then, similarly as to above, N_T is standard transparent and entirely up to the eNB implementation. But typically it would correspond to the number of transmit antennas assumed in the baseband implementation.

The vectors xk are distributed over the grid of data resource elements belonging to the resource block assignment for the PDSCH. Let k denote the resource element index. The corresponding received NR $\times$ 1 vector y_k on the UE side after DFT operation can then be modeled as:

$$y_k = \mathbf{H}_k\mathbf{x}_k + \mathbf{e}_k \tag{4.3}$$

where H_k is an $N_R \times N_T$ matrix that represents the MIMO channel and e_k is an $N_{R\times 1}$ vector representing noise and interference. By considering the resource elements belonging to a certain block X_n output from the precoder and making the reasonable assumption that the channel is constant over the block (the block size L is small and the used resource elements are well-localized in the resource element grid), the following block-based received data model is obtained:

$$\begin{aligned}\mathbf{Y}_n &= [\mathbf{y}_{nL}\ \mathbf{y}_{nL+1} \cdots \mathbf{y}_{nL+L-1}] \\ &= H_{nL}[\mathbf{x}_{nL}\ \mathbf{x}_{nL+1} \ldots \mathbf{x}_{nL+L-1}] + [\mathbf{e}_{nL}\ \mathbf{e}_{nL+1} \ldots \mathbf{e}_{nL+L-1}] \\ &= \mathbf{H}_{nL}\mathbf{X}_n + \mathbf{E}_n\end{aligned} \tag{4.4}$$

with obvious notation being introduced. The transmission rank is per definition given by the average number of complex-valued symbols per resource element. Thus, since Q symbols are transmitted over L resource elements, the transmission rank r is obtained as $r = Q/L$.

4.3 MIMO and MRC

The LTE PHY can optionally exploit multiple transceivers at both the base station and UE in order to enhance link robustness and increase data rates for the LTE downlink. In particular, Maximal Ratio Combining (MRC) is used to enhance link reliability in challenging propagating conditions when signal strength is low and multipath conditions are challenging. MIMO is a related technique that is used to increase system data rates.

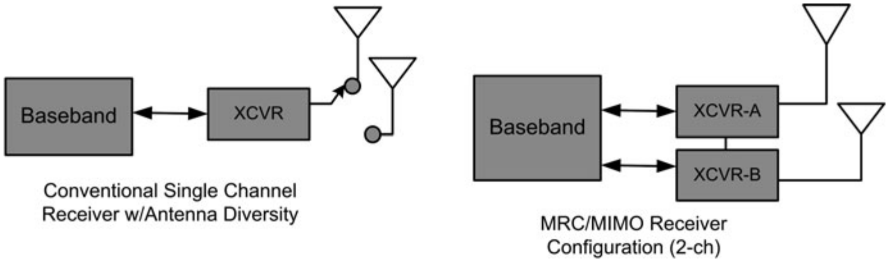

Fig. 4.17 MRC/MIMO operation requires multiple transceivers

Figure 4.17 shows a conventional single channel receiver with antenna diversity. This receiver structure uses multiple antennas, but it is not capable of supporting MRC/MIMO. The basic receiver topology for both MRC and MIMO is shown in the second figure. MRC and MIMO are sometimes referred to as "multiple antenna" technologies, but this is a bit of a misnomer. Note that the salient difference between the receivers shown in the figure is not multiple antennas, but rather multiple transceivers.

With MRC, a signal is received via two (or more) separate antenna/transceiver pairs. Note that the antennas are physically separated and therefore have distinct channel impulse responses. Channel compensation is applied to each received signal within the baseband processor before being linearly combined to create a single composite received signal.

When combined in this manner, the received signals add coherently within the baseband processor. However, the thermal noise from each transceiver is uncorrelated. Thus, linear combination of the channel-compensated signals at the baseband processor results in an increase in SNR of 3 dB on average for a two-channel MRC receiver in a noise-limited environment.

Aside from the improvement in SNR due to combining, MRC receivers are robust in the presence of frequency-selective fading. Recall that physical separation of the receiver antennas results in distinct channel impulse responses for each receiver channel. In the presence of frequency-selective fading, it is statistically unlikely that a given subcarrier will undergo deep fading on both receiver channels. The possibility of deep frequency-selective fades in the composite signal is therefore significantly reduced.

MRC enhances link reliability, but it does not increase the nominal system data rate. In MRC mode, data is transmitted by a single antenna and is processed at the receiver via two or more receivers. MRC is therefore a form of receiver diversity rather than more conventional antenna diversity. MIMO, on the other hand, does increase system data rates. This is achieved by using multiple antennas on both the transmitting and receiving ends.

In order to successfully receive a MIMO transmission, the receiver must determine the channel impulse response from each transmitting antenna. In LTE, channel impulse responses are determined by sequentially transmitting known reference signals from each transmitting antenna as shown in Fig. 4.18.

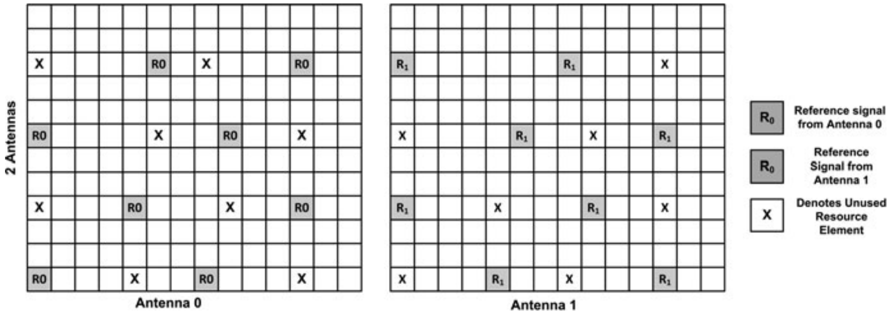

Fig. 4.18 Reference signals transmitted sequentially to compute channel responses for MIMO operation

Referring to the 2×2 MIMO system in Fig. 4.19, there are a total of four channel impulse responses (C1, C2, C3, and C4). Note that while one transmitter antenna is sending the reference signal, the other antenna is idle. Once the channel impulse responses are known, data can be transmitted from both antennas simultaneously. The linear combination of the two data streams at the two receiver antennas results in a set of two equations and two unknowns, which is resolvable into the two original data streams.

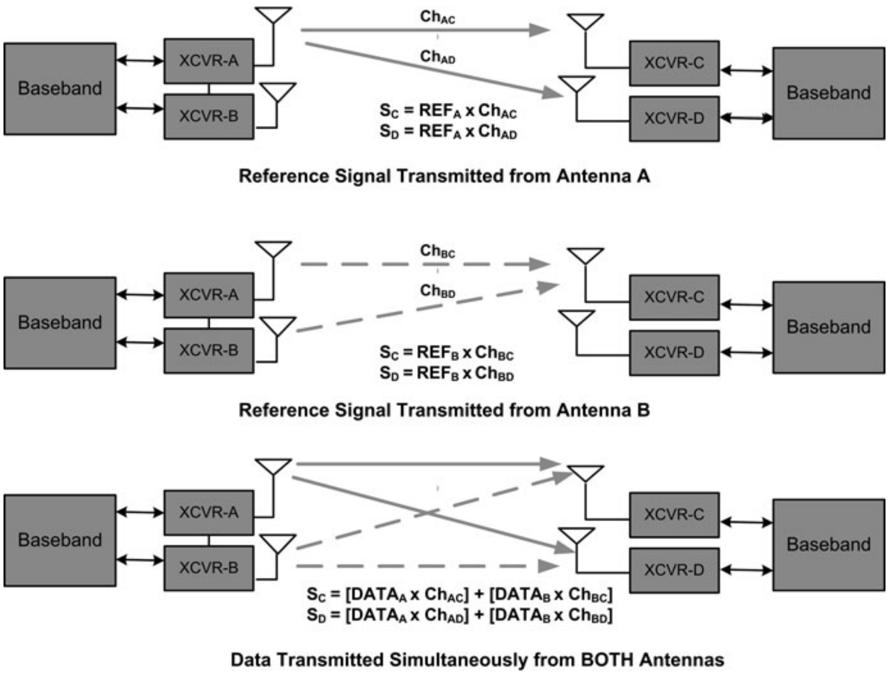

Fig. 4.19 MIMO operation requires a priori knowledge of all channel responses

4.4 Summary and Conclusions

This chapter addressed the advanced radio characteristics of LTE including the following:

- LTE's use of orthogonal frequency division multiple access (OFDMA) and multiple input multiple output (MIMO) in the downlink transmission effectively eliminates intra-cell multiuser interference and minimizes inter-cell multiuser interference, thereby maximizing performance. Similarly, the single-carrier frequency division multiple access (SC-FDMA) uplink transmission allows for user equipment to transmit low power signals without the need for expensive power amplifiers.
- Improvement in battery power consumption in UEs is a side-benefit of the coverage and multipath/power performance advantages offered by LTE.
- Providing the ability to perform two-dimensional resource scheduling (in time and frequency), allowing support of multiple users in a time slot.
- Protecting data against channel errors using adaptive modulation and coding (AMC) schemes based on channel conditions.
- Multiple antennas at the UE are supported with the two receive and one transmit antenna configuration being mandatory.

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